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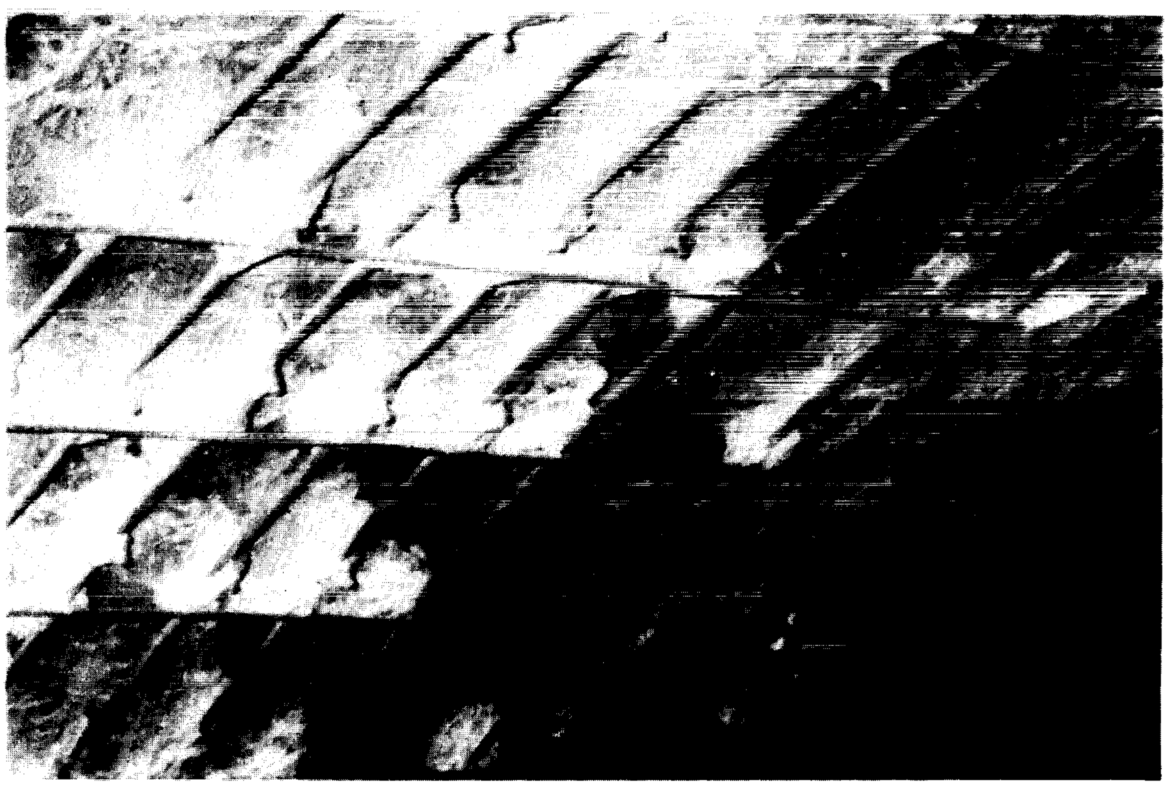
International Workshop on Fire Performance of High-Strength Concrete, NIST, Gaithersburg, MD, February 13-14, 1997 Proceedings

Long T. Phan, Nicholas J. Carino, Dat Duthinh, and Edward Garboczi



COVER

Fire-induced spalling of concrete and buckling of reinforcement
in the Channel Tunnel due to fire on November 18, 1996
(photo by Paul Acker - Laboratoire Central des Ponts et Chaussees, France)

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Editors:

Long T. Phan
Nicholas J. Carino
Dat Duthinh
Edward Garboczi

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-0001

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U.S. Department of Commerce
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EXECUTIVE SUMMARY

A workshop on the fire performance of high-strength concrete (HSC) was sponsored by the Building and Fire Research Laboratory (BFRL), National Institute of Standards and Technology (NIST), on February 13-14, 1997 at NIST facilities in Gaithersburg, Maryland. The organizing committee included Dr. George C. Hoff of Mobil Technology Company, Mr. Michael P. Gillen of Dupont Engineering, Dr. S.K. Ghosh of the Portland Cement Association, and Drs. Nicholas J. Carino, H.S. Lew, and Long T. Phan of NIST. The objective of the workshop was to identify research areas to address issues concerning the fire performance of HSC: namely, (1) the high rate of compressive strength loss of HSC when exposed to high temperature; (2) the high susceptibility of HSC to explosive spalling; and (3) the current inadequacy of code provisions for design of HSC structures exposed to fire. The workshop participants included leading researchers, representatives of trade organizations, government regulators from nine different countries, including Canada, Finland, France, Germany, Norway, Sweden, Taiwan, United Kingdom, and the United States of America.

Following the welcoming remarks by Dr. Jack Snell, Deputy Director of BFRL, the workshop commenced with 13 technical presentations by various researchers. These presentations were followed by four concurrent working group sessions whose objectives were to develop lists of research needs in the topic areas of **material testing**, **element testing**, **analytical studies**, and **codes and standards**. The workshop concluded with a plenary session where recommended research needs were summarized by the four working group Chairmen. The following are summaries of the recommended research needs identified by the four working groups:

Material Tests

(1) *Develop an understanding of the spalling mechanism(s) and establish a predictive parameter and standard test method(s) to measure it.* A parameter that includes concrete properties such as permeability, tensile strength, porosity, and moisture content has been found to be useful in predicting susceptibility to spalling of refractory concrete during the de-watering process prior to exposure to refractory temperatures. A similar parameter is desirable and needs to be developed for use in evaluating spalling potential of fire-exposed HSC. Factors that contribute to the occurrence of spalling need to be understood so that methods to mitigate spalling tendency can be developed.

(2) Measurement of properties of HSC as a function of temperature. Material properties of HSC need to be measured as functions of temperature to provide input data for numerical models. These include mechanical properties (compressive strength, elastic modulus, tensile strength, time-dependent behavior, and fracture mechanics parameters), transport properties (permeability, diffussivity, etc.), thermal properties (thermal conductivity, heat capacity, etc.), sorption isotherms, and water release during dehydration.

(3) Methods for evaluating aggregates for optimizing fire resistance of concrete. Practical methods, based on aggregate characteristics such as coefficient of thermal expansion and physico-chemical reactions leading to volume changes, are needed to evaluate different aggregate sources so that those that can be expected to result in poor performance during fire can be eliminated during the selection of materials for HSC mixtures to be used in critical structural elements.

(4) Methods for evaluation of fire damage. The applicability of advanced techniques based on stress-wave propagation (e.g., acoustic tomography and spectral analysis of surface waves), microwave radiation, and scanning electron microscope (micrographic and chemical analysis) to evaluate the extent of damage after a fire needs to be studied and standards for their used developed.

Element tests

(1) Spalling Mechanisms and Methods to Prevent or Control Spalling. Explosive spalling occurs inconsistently in fire-exposed HSC test specimens and is not completely understood. It is safe to conclude that material tests alone will not suffice in predicting spalling in reinforced structural elements, and element tests will be needed so as to be able to include the effects of reinforcement, cover depth, element size and shape in studying the spalling mechanisms and methods to prevent or control spalling.

(2) Application of Laboratory Test Results to Actual Structures. For normal strength concrete (NSC), laboratory fire tests have been successfully extrapolated to actual structures. However, because the fire performance of HSC is not completely understood and predictable, this cannot yet be done for HSC. Tests, which include scaling laws to account for size effects, are needed to translate reduced scale laboratory tests to full scale prototypes.

(3) Tests of Connections. Individual members are fire tested much more often than entire frames or joints between members, because of the size and cost associated with the latter. However, these tests are necessary for understanding and predicting the behavior of critical areas in HSC structures under fire. This is particularly important in the case of connections between columns of HSC and slabs of NSC.

(4) Determination of Residual Strength. Most structures damaged by fire do not collapse. However, they may have to be demolished because of uncertainty about their residual strength. This is true of NSC and HSC. Much can be learned from post-fire evaluations of residual structural capacity. The effectiveness of repair methods should also be evaluated.

Analytical Studies

(1) Transport Phenomena: (a) Coupled heat and mass transfer leading to pore pressure prediction. The relationships of pore pressure buildup and thermal stresses to the initiation of spalling of HSC need to be studied. The observed success of polypropylene fibers in reducing spalling suggest that pore pressure buildup is a significant factor in the spalling phenomenon. Modeling the heat and mass transfer in HSC should be done to gain an understanding of the spalling process and how fiber can be used to reduce this tendency.

(2) Transport Phenomena: (b) Investigation of new numerical methods to handle the saturated-unsaturated interface zone. The success of different numerical techniques in handling numerical modeling difficulties that occur at the sharp liquid-vapor interface (saturated-unsaturated) zone in concrete when heat is applied needs to be studied.

(3) Thermal stress analysis with inclusion of fracture mechanics. Analysis of internal stresses in HSC elements, caused either by thermal stresses or pore pressure buildup, with consideration of other factors such as creep and shrinkage, must be made in order to determine the relative importance of thermal stresses and pore pressure on the tendency for spalling. A fracture mechanic approach may be needed.

(4) Coupling of pore pressure and fracture process. Accurately measuring and predicting pore pressure buildup during a fire situation is not enough. Experimental data showing that pore pressure does not drop to zero when a crack forms led to a new approach in analyzing the initiation of spalling. Thus modeling to predict spalling should include the effect of cracking and interaction between the pore pressure and the crack.

Codes and Standards

(1) Standard Test Protocols for Engineering Properties of Fire-Exposed HSC. Internationally accepted protocols for fire testing of HSC, which include guidelines for data collection and reporting, need to be developed to ensure compatibility of results from different test programs.

(2) Mechanical Properties-Temperature Design Curves for HSC. Existing design curves for estimating mechanical properties of fire-exposed concrete have been developed based on experimental data of NSC. These design curves have been shown to be unconservative when applied to HSC. Thus, mechanical properties-temperature design curves for HSC at high temperature need to be developed and incorporated into building codes to ensure safety in HSC structures in the event of a fire. Such design curves would also be helpful for assessing the residual strength of HSC structures after a fire.

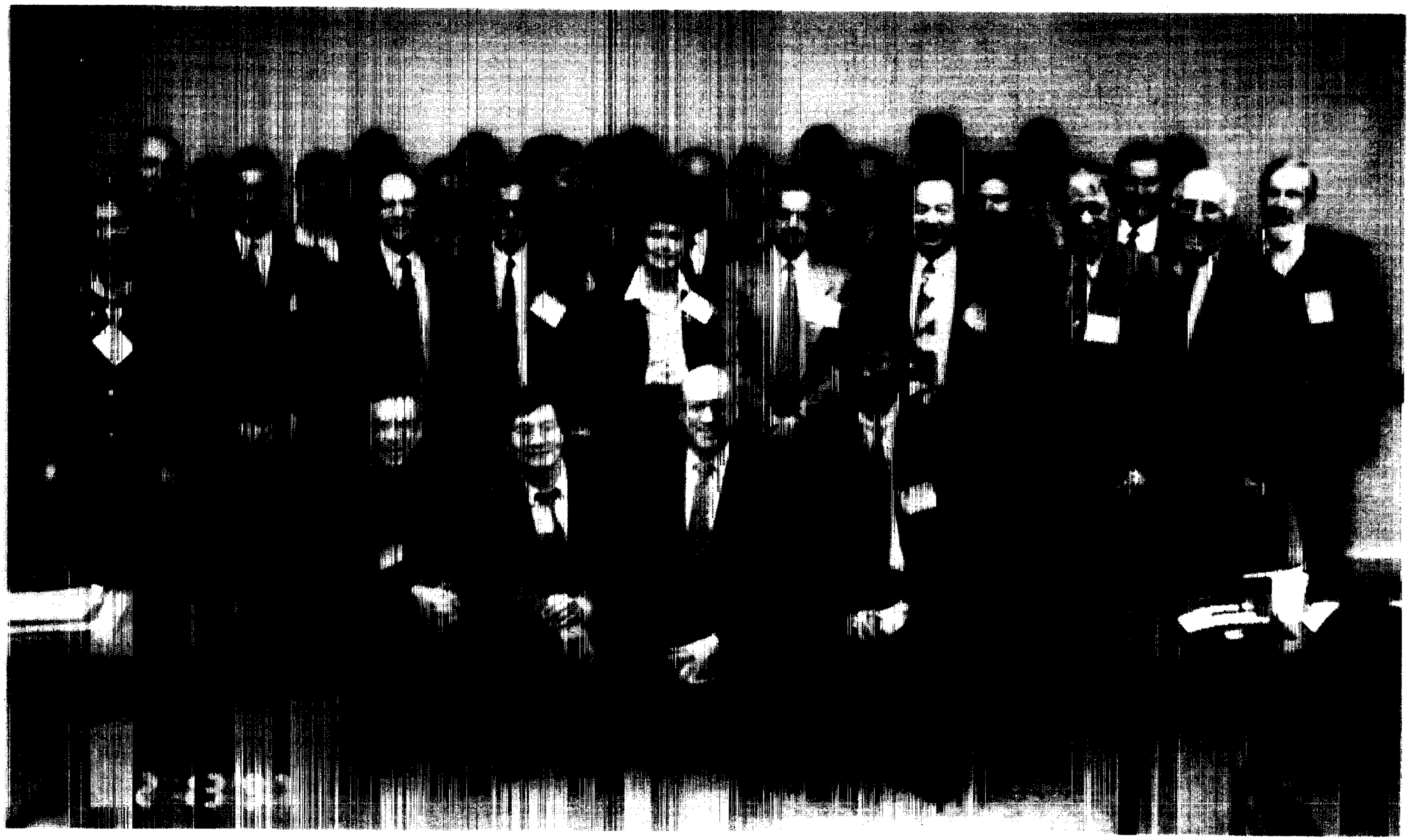
(3) Guidelines for Interpretation of HSC Material Tests and Standard Fire Tests. Engineering properties of HSC at elevated temperature are obtained by testing HSC cylinders or prisms. The measured properties are typically related to the temperature measured at the center of the specimens and are dependent on, among other things, heating rate. Whereas the current standard fire tests, such as ASTM E 119 and ASTM E 1529, prescribe procedures for testing structural assemblies by subjecting them to standard ambient temperature-time histories. These standards characterize the temperature history and duration of exposure inside the test chamber, but not necessarily the temperature and the rate of temperature development within the assemblies. Thus the results of material and standard tests are not directly compatible. Guidelines should be developed to relate the results of these tests.

(4) Guidelines for Selecting Realistic Design Fire Exposures. Current standard fire exposures, prescribed by ASTM E 119 and E 1529, ISO 834, and JIS A 1304, do not represent likely temperature histories of real fires. As a result, the exposure conditions specified in these standard fire test methods are not necessarily representative of the conditions that may exist in real fire scenarios. With the current tendency of moving towards performance-based standards, it is necessary to provide guidance for the selection of realistic design fire exposures which are particularly suitable for the specific HSC structure being evaluated.

(5) Guidelines for Fire Design of HSC Structural Elements. Guidelines for the fire design of HSC structural elements, which allow the calculation or assessment of the fire resistance period and load carrying capacity of structural elements, are not available in U.S. codes and standards. Such guidelines are desirable and should incorporate the different responses due to differences in structural element types (beam, column, wall, or slab), HSC engineering properties, applied loads, and HSC spalling characteristics.

(6) Design Guidelines to Mitigate Spalling in Fire-Exposed HSC. The risk of explosive spalling in HSC elements may be reduced by using appropriate design detailing , such as optimal sizes and spacing of transverse reinforcement, concrete cover, etc., and additions such as steel and polypropylene fibers. The effects of these design details and mixture additions should be studied, and results should be incorporated into design guidelines to reduce the risk of explosive spalling in HSC structures during a fire.

CONTENTS



1. INTRODUCTION

With the recent increase in use of high-strength concrete (HSC) for building and other structural applications, a considerable number of studies, which focus on the material properties as well as the design, manufacturing, and curing aspects of HSC, have been initiated and conducted at various laboratories worldwide. These studies aim to provide technical data for the full exploitation of HSC as a superior construction material compared with the conventional normal strength concrete (NSC). Included in these HSC studies are a limited number of studies on the effect of elevated temperatures on the thermal and mechanical properties of HSC. A subset of the elevated temperature studies includes those where HSC specimens were exposed to increasing temperature and properties were measured as a function of the temperature. These studies, which used a typical heating rate of about 1 °C/min and a maximum temperature of about 800 °C, were designed to provide an understanding of the behavior of HSC when exposed to fire conditions. The results of this group of studies have design implications and were reviewed and reported in NIST publications on the state-of-the-art on the fire performance of HSC [Phan, 1996; Phan and Carino, 1997]. These publications are part of the overall research effort on high performance concrete (HPC) at the National Institute of Standards and Technology (NIST). The NIST publications compiled and compared test data as well as experimental observations reported by various investigators. Specifically, the NIST publications outlined and discussed issues concerning the fundamental differences in material properties between HSC and NSC at elevated temperatures, the increased susceptibility of HSC to explosive spalling when subjected to rapid heating, and the applicability of existing code provisions to fire design of concrete structures made of HSC. Three major findings were identified as a result of this data synthesis:

1. HSC has a higher rate of compressive strength loss at high temperatures compared with NSC. The range of temperatures where this difference is most pronounced is between 100 °C and 400 °C.
2. HSC is susceptible to explosive spalling when exposed to temperatures above 300 °C.
3. Current code provisions for concrete properties at elevated temperatures are unconservative when applied to HSC.

Besides these findings, the NIST publications also identified a shortage of data on a number of issues that are essential for a complete understanding of how HSC would behave at elevated temperatures. The missing data include experimental measurements of tensile strength, pore pressure buildup, and permeability of HSC at high temperatures. Also lacking are data on thermal and mechanical properties of HSC under *stressed test* conditions (the specimens carry load prior to heating, similar to the case of HSC columns in a building during a fire). This shortage of data inhibits effective validation of existing analytical models and limits the development of new ones.

Thus, following the publication of the reports on the state-of-the-art, it was decided to organize a workshop on the fire performance of HSC. Workshop participants were to include researchers and members of academia who have been involved in studies of fire-exposed concrete, as well as practitioners, regulators, and representatives of professional trade organizations who have an understanding of the technical needs concerning the use of HSC. The focus of the workshop would be on research needs to address the technical deficiences associated with fire-exposed HSC. As a result, the Building and Fire Research Laboratory (BFRL) at NIST, in collaboration with industry representatives, which included Dr. S.K. Ghosh of Portland Cement Association, Mr. Michael P. Gillen of Dupont Engineering, and Dr. George C. Hoff of Mobil Technology Company, convened an International Workshop on Fire Performance of HSC in Gaithersburg, Maryland on February 13 and 14, 1997. The workshop participants were comprised of a select group of individuals from nine different countries, including Canada, Finland, France, Germany, Norway, Sweden, Taiwan, United Kingdom, and United States. A list of the workshop participants is provided in Appendix A.2.

In the chapters to follow, the workshop objectives and format are explained and technical presentations made at the workshop are summarized (Chapter 2); the research needs to address the current knowledge gaps concerning fire performance of HSC are described (Chapter 3); and information on worldwide research activities related to the subject of fire performance of HSC are provided (Chapter 4). Finally, papers which accompanied technical presentations made at the workshop are included in Appendix B.

2. NIST WORKSHOP ON FIRE PERFORMANCE OF HSC

2.1 Workshop Objectives and Format

The workshop was intended to provide an open forum where researchers, practitioners, and regulators could exchange expert opinions on current knowledge, technical problems, and design needs concerning the fire performance of HSC. The objective was to identify research areas which would address the unresolved issues concerning the fire performance of HSC as outlined in the NIST report [Phan, 1996]. Fire tests are expensive, and it is not possible for any one agency to perform all of the needed research. Thus a secondary objective of the workshop was to foster a collaborative spirit for potential joint research activities between different agencies, universities, and laboratories. It is hoped that these workshop proceedings will serve as a catalyst for such integrated international research efforts.

The workshop format included: (1) *technical presentations*, (2) *working group sessions*, and (3) a final *plenary session*. Thirteen *technical presentations* were given on the first day of the two-day workshop. The topics included experimental and analytical studies as well as proposed code applications in various countries. This activity was followed by *working group sessions*, which continued to the second day of the workshop. The workshop concluded with a *plenary session* where summaries of the findings were presented by the working group Chairmen. These findings form the basis for these workshop proceedings.

Four working groups were organized based on four research topics: *Material Tests* (Working Group A-1), *Element Tests* (Working Group A-2), *Analytical Studies* (Working Group B), and *Codes and Standards* (Working Group C). Each working group had a Chair and co-Chair to facilitate discussion. NIST staff attended each working group session to serve as a liaison and help record the discussion. The membership of each working group was selected in advance by individual participants based on their interests in the working group topics. The agenda for the workshop is listed in Appendix A.1, and a list of workshop participants by working group is given in Appendix A.3.

Section 2.2 summarizes the technical presentations and includes brief biographies of the presenters. Of the thirteen authors who made technical presentations at the workshop, nine followed up with papers. These papers are included with minimal editorial changes in Appendix B of these proceedings. In addition, a summary of the research efforts at Milan University of Technology, which was submitted by Drs. R. Felicetti and P. Gambarova who were invited but were not able to attend the workshop, is also included in Appendix B. Workshop findings are presented in Chapter 3.

2.2 Workshop Presentations

2.2.1 High-Strength Concrete in Germany - Utilization, Research and Standardization Presenter: Ulrich Diederichs, Amtliche Materialprüfanstalt für das Bauwesen, Germany.

About the presenter:

Dr. Ulrich Diederichs is a physicist at Amtliche Materialprüfanstalt für das Bauwesen of the Institut für Baustoffe, Massivbau und Brandschutz (IBMB/MPA). IBMB/MPA is the largest building materials testing and research institute in Northern Germany and is a non-profit institute of the Technical University of Braunschweig, operating under the auspices of the Lower Saxony State Ministry of Economics and Trade and the Ministry of Science and Culture. His main fields of research included: behavior of concrete at high temperatures, microstructure of building materials, building materials physics, fire resistance of HSC structures, and behavior of concrete for prestressed nuclear reactor vessels under accidental and service conditions. He was a member of RILEM TC PHT-44 "Properties of Materials at High Temperatures," RILEM TC FMC-50 "Fracture Mechanics of Concrete," and RILEM TC MHT-129 "Test Methods of Mechanical Properties of Concrete at High Temperatures."

Summary of presentation:

A summary of Germany's effort in utilization, research, and standardization of HSC was presented. Due to environmental demands for high durability and structural demands for higher compressive strength in new building constructions, HSC is being used more and more in Germany. The German Standard DIN 1045 defines HSC as concrete with average cube compressive strength exceeding 55 MPa (strength class B 55). To meet classification, reinforced HSC structural elements and plain concrete cylinders had to pass fire resistance tests performed by specialists. Many of the fire tests were performed at the Technical University of Braunschweig. Some of the specimens were pre-dried for 6 to 8 weeks at 60 °C, and all were exposed to the ISO 834 standard fire curve. Despite this treatment, severe spalling occurred. Explosive spalling was also observed in many small, 80mm dia. x 700mm, cylinders, made with and without silica fume, after the temperature within the specimens reached 350 °C. In structural element tests, anti-spalling mesh and steel fibers were also used as protection against spalling. The anti-spalling mesh is currently required by DIN 4102, Part 4/03.94 for fire safety on the exposed sides of structural elements. This anti-spalling mesh must be installed with a nominal concrete cover of at least 15 mm if the elements are in normal environments. For elements in moist and/or chemically agressive environments, this nominal concrete cover is to be increased by 5 mm. These spalling mitigation techniques, however, were observed in experiments at the Technical University of Braunschweig to be ineffective..

The results of fire tests on structural elements were incorporated into a set of guidelines of the Deutscher Ausschuss für Stahlbeton, which is a supplementary standard for the German DIN 1045 (*DAfStb-Richtlimie für hochfesten Beton - Ergänzung zu DIN 1045/07.88 für die Festigkeitsklassen B 65 bis B 115*). The current version of these guidelines (August 1995) provides design information, such as fire endurance and load carrying capacity of columns, beams, and walls, made of HSC of strength classes up to B 95. For HSC with compressive strength exceeding 95 MPa, additional tests and requirements must be met prior to use. According to the guidelines, spalling tendency must be counteracted by an antispalling mesh or other means (e.g., addition of polypropylene fibers). At present, the Technical University of Braunschweig is conducting fire tests on concrete tunnel linings made with HSC.

2.2.2 Fire Test of Normal-Weight/High Performance Concrete in Taiwan
Presenter: T.D. Lin, Architecture and Building Research Institute, Taiwan

About the presenter:

Dr. T.D. Lin is currently the president of Lintek International Inc. and a consultant to the Architecture and Building Research Institute in Taiwan. He was formerly with the Portland Cement Association (PCA) and is a pioneer in lunar concrete research. He was a select member of the U.S. delegation to the 1980 U.S.-Soviet Joint Seminar on "Mathematical Computations of Heat Flow." His recent work includes a new method for producing concrete using steam to cause hydration of a dry cement mixture, which results in concrete with twice the compressive strength in 18 hours than that of companion concrete made with the conventional wet procedure. Dr. Lin was the chairman of the ACI Lunar Concrete Committee (ACI 125) and is a member of the Fire Resistance and Fire Protection of Structures Committee (ACI-TMS 216) and ASCE's Fire Safety Committee. He is the recipient of many awards and honors for his research in concrete technology.

Summary of presentation:

The text of Dr. Lin's presentation is printed in Appendix B, Section B.1.

2.2.3 Fire Resistance and Residual Strength of HSC Exposed to Hydrocarbon Fire
Presenter: Jens Jacob Jensen, SINTEF, Norway.

About the presenter:

Dr. Jensen is a senior research engineer at SINTEF Civil and Environmental Engineering, Cement and Concrete Division in Trondheim; Norway. SINTEF is a research organization with about 2000 employees and closely connected to the University of Trondheim. Dr. Jensen's main areas of emphasis are structural mechanics, structural dynamics, reinforced concrete design, high strength concrete, tension structures, protective structures, bridges, and offshore structures. He has conducted a number of projects concerning the fire resistance of high strength concrete structures.

Summary of presentation:

The text of Dr. Jensen's presentation is printed in Appendix B, Section B.2.

2.2.4 Spalling Phenomena of HPC and OC
Presenter: Yngve Anderberg, Fire Safety Design (FSD), Sweden

About the presenter:

Dr. Anderberg is presently the managing director of Fire Safety Design (FSD) in Sweden and director of FSD in the U.K., a practice he founded in 1977. He is a frequent speaker at international conferences, has published numerous papers on fire safety engineering and is a member, secretary, and chairman of several European committees and working groups, including the Swedish Concrete Association, RILEM, CIB W14, the Swedish Fire Protection Association, the Society of Fire Protection Engineers (USA), the Institute of Fire Safety (UK), and Firepro Institute Ltd., which engaged in the advancement of fire protection techniques. He is the Swedish specialist on fire engineering design for concrete and steel constructions within CEN and has been responsible for building fire safety solutions for more than 1000 projects in Sweden as well as in Europe since 1977. Dr. Anderberg has been responsible for and actively involved in the assessment of fire safety of 10 offshore platforms, including the Hibernia, Ekofisk, Njord, and Visund.

Summary of presentation:

Dr. Anderberg's presentation is printed in Appendix B, Section B.3.

2.2.5 Fire Damage in the Eurotunnel
Presenter: Franz-Josef Ulm, Laboratoire Central des Ponts et Chaussees (LCPC), France.

About the presenter:

Dr. Ulm is a research engineer in the concrete department at the Laboratoire Central des Ponts et Chaussees (LCPC), Paris, of the French Ministry of Public Works. He lectures on continuum mechanics, structural dynamics and materials science at Ecole Normale Superieure de Cachan, Ecole Centrale de Paris, Technische Universitat Muenchen (FRG), and is Professor at the Federal University of Rio de Janeiro (COPPE/UFRJ, Brazil).

Summary of presentation:

A brief summary was presented of fire damage to a section of the 52-km long Channel Tunnel connecting Britain and France, caused by a fire on November 18, 1996, and LCPC's repair work.

The incident occurred when a fire broke out on a shuttle train carrying freight trucks that was en route from France to England through one of the Channel Tunnel's two transport tubes. The fire was reported to have lasted for about 10 hours, and the temperature of the fire was estimated to have reached between 1000 °C to 1200 °C. The flames and intense heat severely damaged both the concrete and reinforcing mesh of a portion of one of the two transport tubes. The damaged portion of the 450 mm thick tunnel ring was about 40 m in length. The concrete used did not contain silica fume and was designed to have compressive strength of about 50 MPa. However, post-fire testing on the undamaged concrete indicated actual compressive strength of about 100 MPa. Fortunately, the damaged section was surrounded by solid bedrock, which prevented water from entering the tunnel at places where full-depth spalling occurred.

For most of the damaged section, fire induced spalling, up to a depth of 150 mm to 200 mm, was observed with an estimated spalling rate of 1mm/minute. Local buckling due to exposure to fire after the concrete spalled off was observed for some sections of the reinforcing grid, and a loss of about 40% of the reinforcement's yield strength was observed for other sections. The reinforcing grid was found to provide some restraint for the concrete even though it was not actually designed as anti-spalling mesh. The repair involved the use of fiber reinforced shotcrete. The tunnel was closed for 6 months, at an estimated revenue loss of about $1.5 million a day.

2.2.6 Research Activities in Finland on Fire Resistance of HSC
Presenter: Ulla-Maija Jumppanen, VTT Building Technology, Finland

About the presenter:

Ms. Jumppanen is a senior research scientist at the Fire Technology Laboratory of the Valtion Teknillinen Tutkimuskeskus (VTT, Technical Research Center of Finland). She has conducted research and written extensively on the subject of properties of fire exposed concrete. A detailed biography of Ms. Jumppanen is not available at this writing.

Summary of presentation:

A brief summary was presented of research activities in Finland on the fire resistance of HSC and ultra HSC (UHPC, concrete with compressive strength exceeding 150 MPa). These research activities are in support of research activities of the European BRITE EURAM program (HITECO), which was created in 1996 to promote the understanding and industrial applications of high performance concretes in high temperature environments, and in which VTT is a partner. The following aspects of HSC are investigated in this program:

- Concrete strength: HSC (C60 - 100) and UHPC
- Thermal stability of materials:
  - Thermal expansion
  - Porosity
  - Acoustic emission analysis
- Mechanical behavior:
  - Stress-strain relationships
  - Total deformation
  - Effect of restraint forces
- Spalling
  - Small specimen
  - Column tests
- Tests on short columns
- Tests on structural members
- Material model for fire exposed HSC

Other partners of the BRITE EURAM program include Bouygues (France), ENEA (Italy), Aalborg (Denmark), Imperial College (England), PARTEK (Finland), CSIC (Spain), and PADOVA (Italy).

Program duration is 3 years (1996-1998). Program deliverables include software, studies of spalling and mechanical behavior, and prenormative recommendations. The National Building Code of Finland for Concrete Structures (Rak MK B4) is one of only a few building codes at present that prescribes a strength reduction curve as a function of temperature specifically for HSC (concrete strength classes of K70 to K100), and a compressive capacity curve for HSC columns as a function of fire duration (applicable up to 120 minutes of fire exposure).

2.2.7 Studies on the Fire Resistance of HPC at the National Research Council/Canada Presenter: Venkatesh Kumar R. Kodur, National Research Council-Canada (NRCC), Canada

About the presenter:

Dr. Kodur is a research associate at the National Fire Laboratory of the National Research Council in Canada. His expertise is in the areas of laboratory testing and numerical analysis for the evaluation of fire resistance of structural members, and non-linear design and analysis of concrete and steel structures. He is a member of many professional committees, including the ASCE's Fire Protection Technical committee, the Underwriter Laboratories of Canada Task Group on Fire Endurance Tests, and the Canadian Standards Association Technical Committee on FRP Structural Components for Buildings. Dr. Kodur has written or co-authored many articles on the fire resistance of structural members.

Summary of presentation:

Dr. Kodur's presentation is printed in Appendix B, Section B.4.

2.2.8 Spalling of High-Strength LWA Concrete - Cause and Cure Presenter: M.P. Gillen, Dupont Engineering, U.S.A.

About the presenter:

Mr. Gillen is a Consultant (Engineer) at DuPont Engineering in the Civil Engineering Systems group, with responsibility for providing technical support on concrete design, construction, and repair for DuPont and Conoco facilities. Prior to this position, he was Project Engineer - Concrete on Conoco's Heidrun Tension Leg Platform project in Norway (1992-1994). His past work experience includes ten years as engineer in the Portland Cement Association Fire Research Section, 3 years with Rockwell as concrete/geomechanics laboratory manager at DoE's Hanford facility, and 4 years as research engineer for Conoco's Production R&D Division. He is presently a member of ACI committees on Fire, Corrosion, Nuclear and Hazardous Waste, Offshore Structures (former Chair), and Lunar Concrete.

Summary of presentation:

The Heidrun offshore tension leg platform in Norway is a unique floating platform made with lightweight concrete. The concrete was designed with a design life of 50 years in the North Sea, contained 3% to 4% of silica fume, and had a design compressive strength of 60 MPa. High water pressure exposure tests, done at SINTEF in Norway, showed that the Heidrun platform concrete has extremely low permeability. In fact, after 144 days of exposure to high water pressure, only one aggregate diameter of penetration by the water was observed compared with complete saturation of a 83 MPa normal density concrete after the same exposure. Unfortunately, the unintended effect of low permeability is high vulnerability to fire damage. Upon exposure to a simulated hydrocarbon fire, the Heidrun platform concrete disintegrated due to spalling.

To remedy the increased spalling vulnerability of the Heidrun platform concrete, Conoco initiated a project to study the effects of different variables such as moisture content, curing regimes, and inclusion of steel or polypropylene fibers. The test program consisted of 12 concrete prisms, 300 mm x 300mm x 1500 mm in size. Some specimens were dried at approximately 60 °C for a month prior to exposure to hydrocarbon fire. One specimen was dried at 105 °C until free moisture was completely eliminated. Other specimens included either steel or polypropylene fibers at 0.1% to 0.2% by volume. The lengths of polypropylene fibers varied from 12 mm to 20 mm.

The test results indicated the important role of moisture in the spalling phenomenon. Explosive spalling was observed in specimens pre-dried at 60 °C (moisture was not completely eliminated), and in moist specimens with steel fibers (steel fibers increased the tensile strength of the concrete but resulted in spalling of larger pieces of concrete). However, no spalling was observed in the specimen that was completely predried at 105 °C and in moist specimens that contained polypropylene fibers. Polypropylene fibers with lengths between 150 mm to 200 mm were found to be most effective for the Heidrun concrete. The study concluded that:

- The primary culprit for spalling is moisture.
- Stress and restraint has an influence on the spalling behavior.
- Polymeric fiber addition reduces spalling and offers a tremendous financial advantage over fire protection by passive coatings or other means.

2.2.9 Limitations of Current U.S. Standards and Challenges of Proposed Performance-Based Standards

Presenter: J.A. Milke, Department of Fire Protection Engineering, University of Maryland

About the presenter:

Dr. Milke is an Assistant Professor in the Department of Fire Protection Engineering at the University of Maryland. He has a Ph.D. in Aerospace Engineering and M.S. in Mechanical Engineering, both from the University of Maryland and B.S. degrees in Physics from Ursinus College and Fire Protection Engineering from the University of Maryland. Recently, his research activities have included a description of the sensing mechanisms for a smart fire detector, analysis of water mist fire suppression systems, smoke management and structural fire protection. He is active in several professional societies, including the National Fire Protection Association, Society of Fire Protection Engineers, International Association of Fire Safety Science and American Society of Civil Engineers. Dr. Milke has numerous publications in the fire protection field, principally in the areas of structural fire protection and smoke management.

Summary of presentation:

The text of Prof. Milke's presentation is printed in Appendix B, Section B.5.

2.2.10 Computational Modeling of Temperature, Pore Pressure, and Moisture Content in Concrete Exposed to Fire
Presenter: G. Ahmed, Portland Cement Association (PCA)

About the presenter:

Dr. Ahmed is a Fire Research Engineer at Portland Cement Association in Skokie, Illinois. His primary research activity is in developing heat/mass transfer models for applications to concrete exposed to elevated temperatures. A detailed biography of Dr. Ahmed is not available at the time of this writing.

Summary of presentation:

The text of Dr. Ahmed's presentation is printed in Appendix B, Section B.6.

2.2.11 Analysis of Pore Pressure, Thermal Stress, and Fracture of Concrete in Rapidly Heated Concrete
Presenter: Z.P. Bažănt, Department of Civil Engineering, Northwestern University.

About the presenter:

Born and educated in Prague, Dr. Zdeněk P. Bažant became a professor at Norwestern University in 1973, was named in 1990 to the distinguished W.P. Murphy Chair, and served during 1981-87 as Director (founding) of the Center for Concrete and Geomaterials (a predecessor to the current Advanced Cement Based Material Center). He has authored numerous journal articles and books on stability of structures (1991), concrete at high temperatures (1996), and creep of concrete (1996). He served as Editor (in Chief) of the ASCE Journal of Engineering Mechanics (1988-1994) and is Regional Editor of the International Journal of Fracture. He was founding president of IA-FraMCos, and president of the Society of Engineering Science. He has chaired many technical committees in ASCE, RILEM, and ACI, and is the recipient of numerous awards. He is a Fellow of the American Academy of Mechanics, ASME, ASCE, and ACI, and in 1996 was elected to of the National Academy of Engineering.

Summary of presentation:

Dr. Bažănt's presentation is presented in Appendix B, Section B.10.

2.2.12 Fire Tests on Normal and High-Strength Reinforced Concrete Columns
Presenter: Corina-Maria Aldea, Northwestern University

About the presenter:

Dr. Aldea is a post-doctoral research fellow at Northwestern University, National Science Foundation Center for Science and Technology of Advanced Cement Based Materials, where she was a Fulbright visiting research fellow in 1995-1996. She was a senior assistant professor and head of the French Division of the Department of Engineering Sciences of the Technical University of Civil Engineering in Bucharest, Romania. Her current research areas focus on cement based materials. Most recently she has been involved in studying transport properties in order to quantify concrete durability.

Summary of presentation:

Dr. Aldea's presentation is printed in Appendix B, Section B.7.

2.2.13 Measurement and Prediction of Pore Pressure in Cement Mortar Subjected to Elevated Temperatures

Presenter: Gary Consolazio, Rutgers University.

About the presenter:

Dr. Consolazio is a professor in the Department of Civil and Environmental Engineering at Rutgers University, and is an active participant in the Center for Advanced Infrastructure Technology located at Rutgers. His current research areas focus on modeling and measurement of heat and mass flow through concrete at elevated temperatures and pressures, and on the application of finite element analysis techniques to vehicle impact simulation. Most recently he has been involved in the measurement and numerical prediction of pore pressures and temperatures in moist cement mortar specimens subjected to high temperature radiant heating.

Summary of presentation:

The text of Dr. Consolazio's presentation is printed in Appendix B, Section B.8.

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3. RESEARCH NEEDS IDENTIFIED BY WORKING GROUPS

The working groups were tasked with identifying research needs within the working group topics that would lead to a better understanding of the fire performance of HSC. Each of the working groups was free to select its own discussion format. In general, the working groups started with free discussion to arrive at a consensus on knowledge gaps relevant to the topics of the working groups and, towards the end of the working group sessions, used the identified knowledge gaps to formulate lists of research needs. The following sections list the research needs that were developed by the four working groups. Even though some similarities exist between lists, the NIST editors decided not to consolidate research needs into a single list, since these similarities reflect the importance of some research needs to more than one working group.

3.1 Working Group A-1: Material Tests

3.1.1 Introduction

This working group addressed research needs related to understanding the effects of short-term elevated temperatures on the mechanical, thermal, and mass transport properties of HSC. The working group was composed of the following individuals:

Y. Anderberg (Chair)	Fire Safety Design	Sweden
L. Bell	FiberMesh	USA
A. Bilodeau	CANMET	Canada
N.J. Carino (Recorder)	NIST	USA
J.R. Clifton	NIST	USA
M. Gillen	DuPont Engineering	USA
U-M. Jumppanen	VTT	Finland
R.E. Moore	Univ of Missouri-Rolla	USA
T. Sander	Univ of Missouri-Rolla	USA

First, the group identified those areas in which there is a serious lack of knowledge related to the materials performance of HSC when exposed to high temperatures. Input from workshop invitees, that were provided prior to the workshop, were reviewed. Based on that information and the personal knowledge of working group members, the following were found to be the areas where there are significant knowledge gaps:

(1) Spalling mechanism and methods to prevent or control spalling

This is by far the most important knowledge gap in the fire performance of HSC. As reviewed in the NIST state-of-the-art report [Phan 1996], spalling has been observed in some but not all high-temperature tests of HSC. It is generally believed that spalling results from the buildup of internal pressure due to the transformation of water to vapor. The pressure buildup is believed to result from the extremely low permeabilities of concretes with low water-binder ratios. However, thermal gradients may also play a role in the development of internal stresses that contribute to the spalling phenomenon. While progress has been made in modeling heat conduction and mass transport in concrete subjected to high external temperature, additional work is needed to link these calculations to the buildup of internal stresses and to verify the accuracy of model predictions. When a verified model has been developed, it can be used in parametric studies to determine the effects of different conditions on the internal state of stress (or strain) during fire exposure. A useful outcome of the parametric study would be to identify those conditions that minimize the possibility of spalling during a fire, including an explanation of why the addition of polymeric fibers has been found to reduce the severity of spalling.

(2) Properties of HSC as a function of temperature

In order to be able to predict the performance of a reinforced concrete structure during a fire, it is necessary to know how the properties of concrete are affected by temperature. These properties include the "constitutive properties" such as ultimate strength and stress-strain behavior, and other "material properties," such as thermal and mass transport properties. The latter properties are essential for developing a material model to predict the buildup of internal stress (or strain) during heating.

(3) Effects of composition and processing variables on the performance of HSC at elevated temperature

To produce concrete that is least susceptible to damage during fire, it is necessary to understand how changes in composition and processing affect performance. Since there are numerous possible combinations of materials, proportions, and processing conditions (curing methods, maturity at time of fire exposure, etc.), a model to predict performance for a given set of parameters would be an efficient means for identifying those conditions that would result in the best performance. Limited testing could be used to verify model predictions.

(4) International standard test methods

A major problem in comparing data on fire performance from different laboratories is the lack of common test methods. RILEM Committee 129-MHT on Test Methods for Mechanical Properties of Concrete at High Temperatures is in the process of developing a set of recommendations that may provide the basis for future international standards.

In experimental assessments of the performance of concrete exposed to elevated temperature, several key features of the test methods need to be considered in order to interpret and compare results [Phan 1996; Anderberg 1983]. These include:

- temperature distribution in the test specimen during the measurement of material properties,

- relationships between temperature and load histories, and
- type of loading.

The nature of the temperature distributions during testing can be characterized by considering two groups of tests:

- *Steady-state test*—The specimen is heated slowly to a target temperature; the external temperature is held constant to allow the internal specimen temperature to reach a uniform value; the properties are measured after a uniform internal temperature is reached.
- *Transient test*—The specimen is exposed to an ambient temperature that increases at a relatively fast rate so that temperature gradients exist in the specimen during the test. During the heating, the specimen could be subjected to a constant load or a constant deformation (restraint provided).

Steady-state tests are better suited for measuring the effects of temperature on material properties, and transient tests are better suited for investigating behavior under conditions that may be encountered during an actual fire. Thus transient tests are usually used for tests of structural elements.

In addition to the temperature distribution during testing, another important feature of elevated temperature tests is the relationship between temperature and loading histories. For steady-state tests, three types of tests are commonly used to characterize the effects of temperature on material properties:

- *Unstressed test*—The specimen is heated to the target temperature in the absence of stress, and the specimen is loaded after a steady-state condition has been reached.
- *Stressed test*—The specimen is loaded at room temperature to a fraction of its room temperature strength; the specimen is heated to a target temperature; and, after a steady-state condition is reached, the specimen is tested.
- *Residual property test*—The specimen is heated to a target temperature and maintained until a steady-state condition is reached, then it is cooled to room temperature, and tested at room temperature.

These three types of steady-state tests are illustrated in Fig. 3.1, in which the upper graphs are schematics to show the temperature histories and the lower graphs show the loading histories.

Finally, different methods of loading are possible to measure mechanical properties. These include:

- *Stress-rate control*—The stress is increased at a constant rate.
- *Strain-rate control*—The strain is increased at a constant rate.
- *Constant stress (creep)*—Stress is maintained constant and deformation is measured as a function of time.
- *Constant strain (relaxation)*—Strain is maintained constant and stress is measured as a function of time.

The first two of these are commonly used to develop the stress-strain relationship of the concrete. However, the most common loading method is using strain (or deformation) control, because of the instability that occurs in stress-rate controlled tests as ultimate capacity is approached. The latter two types of loading are used to measure time-dependent response, and these may be of limited importance considering the relatively short duration of a fire.

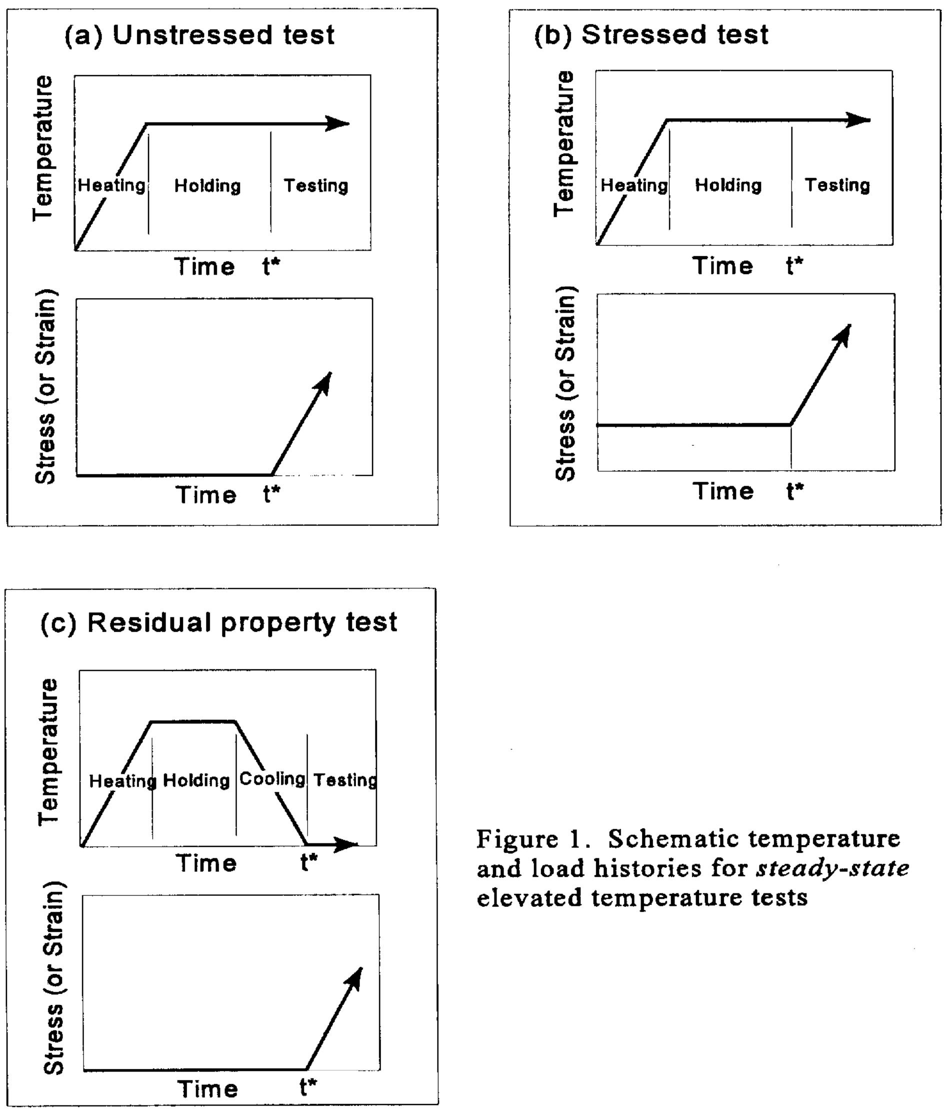

Figure 1. Schematic temperature and load histories for *steady-state* elevated temperature tests

(5) Methods for evaluating performance of local aggregates

Aggregate properties are known to have a strong influence on the performance of concrete during a fire. However, there are no standard procedures for the selection of the suitable aggregate for improved fire performance. Simple tests or selection criteria would be helpful in evaluating the suitability of a particular aggregate.

(6) Guidelines for evaluation of fire-damaged structures

While not restricted to HSC, there is a need for standard practices to permit economical and reliable evaluation of the extent of damage due to fire. Such information is vital for evaluating the safety of a structure exposed to a fire and for delineating the extent of damage in order to develop a repair strategy. The working group felt that this topic could also fall under the domain of the "element tests" group.

3.1.2 Research Needs

The following research areas were discussed in relation to the above-mentioned knowledge gaps. Each research area is followed by a brief discussion of the scope of required work.

(1) Develop an understanding of the spalling mechanism(s) and establish a predictive parameter and standard test method(s) to measure it

Discussion: It would be desirable to develop a parameter that could be used to evaluate the spalling potential of HSC when exposed to fire. In the area of refractory concretes, it has been found that a parameter that includes permeability, tensile strength, porosity, and moisture content has been found to be useful in predicting susceptibility to spalling during the de-watering process prior to exposure to refractory temperatures. A combination of experimental and analytical studies will likely be needed to gain the understanding to develop this parameter.

In order to validate the results of analytical predictions of stresses leading to spalling, experimental data are needed. Such data might include measurement of internal pore pressures and moisture distributions during heating of a test specimen.

A major component of the research will involve studies of the effects of compositional and processing factors (curing methods, maturity, self-desiccation) on spalling tendency. In addition the effects of other factors, such as magnitude of thermal gradients, reinforcement location, geometrical constraints, size, and presence of stress on spalling tendency should be considered. Also, the effects of thermal exposure conditions (rate of temperature rise, maximum temperature, direct exposure to flames, and uniformity of exposure conditions) should be examined. The results of this work should allow understanding of why spalling has not always been observed in tests of HSC.

When the factors that contribute to occurrence of spalling are understood, it should be possible to develop methods to mitigate spalling tendency. Included among potential methods would be the use of "sacrificial" synthetic fibers and "reinforcing" steel fibers. The long-term product would be the development of recommended guidelines or practices for producing HSC that will resist spalling when exposed to fire.

(2) Measurement of properties of HSC as a function of temperature

Discussion: Knowledge of HSC properties ("intrinsic") at high temperatures forms the foundation for evaluating the performance of fire-exposed reinforced concrete elements. In order to permit the comparison of data from different research programs, it will be necessary to establish a suite of standard test methods. In developing these methods, distinctions will need to be made between transient and steady-state tests. Also, distinctions are needed between properties measured at high temperatures versus those measured at room-temperature after heating (residual properties). Guidelines will need to be developed on which types of tests should be used for different purposes. Factors such as maturity and conditioning prior to testing need to be studied and standardized.

Past studies have focused on the effects of temperature on compressive strength and elastic modulus. However, the scope of future studies should be expanded to include other mechanical properties such as tensile strength, time-dependent behavior, and fracture mechanics parameters. Splitting tensile tests have been found to be useful in studies of refractory concretes and should be applied to HSC.

Methods should be established for determining relationships between mechanical properties and microstructural changes (porosity, pore structure, nature of interfacial zone, and microcracking). The effects of specimen shape and size and of previous load histories on measured properties should also be understood.

In addition, other material characteristics need to be measured as functions of temperature to provide input data for numerical models. These other characteristics include transport properties (permeability, diffussivity, etc.), thermal properties (thermal conductivity, heat capacity, etc.), sorption isotherms, and water release during dehydration.

(3) Methods for evaluating local and manufactured aggregates for optimizing fire resistance of concrete

Discussion: Practical methods are needed to evaluate different aggregate sources so that those that can be expected to result in poor performance during fire can be eliminated during the selection of materials for HSC mixtures to be used in critical structural elements. Characteristics such as coefficient of thermal expansion and physico-chemical reactions leading to volume changes need to be understood. In addition, methods are needed to identify aggregates with bound water that can be released during fire exposure and contribute to the development of internal pressure.

(4) Methods for evaluation of fire damage

Discussion: There have been advances in nondestructive testing methods to evaluate concrete. There should be investigations of the applicability of advanced techniques based on stress-wave propagation (e.g., acoustic tomography and spectral analysis of surface waves) and microwave radiation to evaluate the extent of damage after a fire. Other techniques based on the scanning electron microscope (micrographic and chemical analysis) should be developed for more in-depth analysis of microstructural damage or changes of samples taken from the affected structure.

3.2 Working Group A-2: Element Tests

3.2.1 Introduction

The working group addressed research needs related to the effects of short term, high temperatures on the behavior, load bearing capacity and structural integrity of various structural elements, such as columns, beams, slabs, wall panels, etc., made of high strength concrete. The working group was composed of the following individuals:

C.-M. Aldea	Northwestern University	U.S.A.
L. W. Bell	Fibermesh	U.S.A.
R. G. Burg (co-Chair)	Construction Technology Lab.	U.S.A.
U. Diederichs (Chair)	IBMB / MPA Braunschweig	Germany
D. Duthinh (recorder)	NIST	U.S.A.
W. L. Gamble	Univ. Of Illinois, Urbana-Champaign	U.S.A.
G. C. Hoff	Mobil Technology	U.S.A.
J. J. Jensen	SINTEF	Norway
U. M. Jumppanen	VTT Building Technology	Finland
V. Karthigeyan	HSB-OSD (Health and Safety)	U.K.
V. Kodur	National Research Council	Canada
T. D. Lin	Fire Laboratory	Taiwan

First, the group attempted to establish a definition of high strength concrete which, up to now, varies from country to country. In general, as the concrete compressive strength increases, fire tests are fewer, and less is known about concrete fire performance. Most fire test data are for normal strength concrete, with compressive strength less than 50 MPa. On the other hand, some codes define HSC as concrete exceeding a certain compressive strength (40 MPa for ACI, 55 MPa cube strength for the German Code). Since the water-to-binder ratio[1] can be used to predict the difference in the spalling behavior of NSC and HSC under fire (with $w/b \approx 0.4$ being the transition), it was suggested that the w/b ratio could serve to define HSC for the purpose of fire testing.

3.2.2 Research Needs

(1) Spalling Mechanisms and Methods to Prevent or Control Spalling

Discussion: Explosive spalling has been observed in tests of elements of reinforced HSC and also in cylinder or cube tests (material tests). The phenomenon is not completely understood, and spalling behavior occurs inconsistently, sometimes with two identical specimens heated identically behaving quite differently. Although spalling is undesirable, it is not necessarily catastrophic. It was

[1] Water-binder ratio is widely used in Europe, while in North America the term commonly used is water-cementitious material ratio.

reported that, in a recent panel test, the cover concrete spalled off, but the concrete inside the reinforcement was relatively undamaged. When polypropylene fibers were added to the concrete, their effect was to delay the onset of spalling, which involved larger chunks of concrete when it finally occurred.

Although existing analytical models are not adequate due to the complexity of the phenomenon, it is safe to predict that material tests alone will not suffice in predicting spalling behavior, as the effects of reinforcement and cover depth have shown. Element size and shape are also likely to be important. Element tests are therefore needed to study spalling mechanisms and methods to prevent or control spalling in actual structures.

(2) Application of Laboratory Test Results to Actual Structures

Discussion: For NSC, laboratory fire tests have been successfully extrapolated to actual structures. However, because the fire resistance behavior of HSC is not completely understood and predictable, this cannot yet be done for HSC. As the specimen size, material properties (compressive strength, *w/b* ratio, concrete moisture content) and the reinforcement design change, the behavior also changes.

Clearly, a behavioral model is needed. Also needed is a number of tests to verify and calibrate the model, which should also include scaling laws, i.e., account for size effects in order to translate reduced scale laboratory tests to full scale prototypes.

(3) Development of Test Protocols

Discussion: There is a need to develop international test protocols for fire testing of HSC members. Current standards were developed for NSC and may not be appropriate for HSC. For example, it does not make sense to pre-dry HSC specimen to 75 % relative humidity as is recommended for NSC because this could have a direct effect on the test results.

Guidelines for data collection and reporting should also be established. For example, reinforcement details are important in understanding spalling behavior, and yet are often unreported. Guidelines on measurement of deflections, visual recording of overall behavior, weighing of spalled pieces, etc. would also be most useful. It was suggested that a standards organization, such as NIST, is ideally suited for such a task.

(4) Tests of Connections

Discussion: Individual members, cylinders and cubes are fire tested much more often than entire frames or joints between members, because of the size and cost associated with the latter. However, these tests are necessary for understanding and predicting the behavior of structures under fire. This is particularly important in the case of connections between columns of HSC and slabs of NSC.

(5) Determination of Residual Strength

Discussion: Most structures damaged by fire do not collapse. However, they may have to be demolished because of uncertainty about their residual strength. This is true of NSC and HSC. Much can, and should be learned from post-fire evaluations of residual structural capacity. The effectiveness of repair methods should also be evaluated.

(6) Effects of Fire Extinguishing

Discussion: An example was cited about a building on fire that collapsed when a critical HSC column was doused with cold water and suffered terminal thermal shock. It is a rare fire laboratory that allows investigation of the effect of fire extinguishing measures, because of possible damage to equipment and instrumentation. However, the need is there, to ensure that the remedy is not worse than the disease.

(7) Prioritization of Element Tests

Discussion: HSC is being increasingly used in structural applications. To balance the need for fire safety and the limited resources and cost involved in research, element tests should be prioritized in terms of urgency. Since the most widely used HSC elements are columns, they should be high on the priority list. Questions arise as to the loading (centric or eccentric), fire exposure (symmetrical or asymmetrical), concrete strength, column size and shape, reinforcement design, presence or absence of fibers in the concrete, etc. Doubts were expressed that a sufficient data base exists on the the behavior of HSC (unlike NSC) columns under normal service temperatures. HSC, sometimes with lightweight aggregate, is also increasingly used in precast, prestressed elements and hollow core slabs. Also, there have been more recorded fires in buildings under construction (due to welding, cold weather curing of concrete, etc.), than in completed buildings. So, the fire tests of elements made of young or lightweight, high strength concrete are called for.

It was suggested that NIST, after having reviewed existing data, is in an excellent position to propose such prioritization. In this context, NIST should also review the capability of existing fire laboratories worldwide and compile a detailed description of known future test programs.

3.3 Working Group B: Analytical Studies

3.3.1 Introduction

A comprehensive theoretical understanding of how high temperatures during a fire cause spalling of concrete is not yet known. In general, this knowledge gap is accompanied by the lack of established practical models that can take into account the material properties of concrete and how these properties affect fire performance. Computer models that have some of these capabilities need further development. The charge of this working group was to: identify knowledge gaps for HSC pertinent to its fire performance; and identify research needs for purposes of filling knowledge gaps and complementing the recommended analytical work. Transport phenomena (leading to pore pressure) buildup and thermal stresses are focal points as primary contributing factors of high-temperature induced spalling. Further investigation is needed to determine the relative impact that each of these has on the spalling condition such that a design solution may be developed to reduce or eliminate this event. Members comprising the working group included the following:

J.P. Hurst (Chair)	Portland Cement Association	U.S.A.
E. Garboczi (Recorder)	NIST	U.S.A.
G. Ahmed	Portland Cement Association	U.S.A.
Z.P. Bažănt	Northwestern University	U.S.A.
G.R. Consolazio	Rutgers University	U.S.A.
L. Cooper	NIST	U.S.A.
N. Martys	NIST	U.S.A.
F-J. Ulm	LCPC	France

3.3.2 Research Needs

(1) Transport Phenomena

(a) Coupled heat and mass transfer leading to pore pressure prediction

Discussion: There was a lengthy discussion on whether pore pressure buildup or thermal stresses had a greater impact on the initiation of spalling. After much debate, it remained undetermined, with both requiring further investigation. One of the compelling arguments for pore pressure as a significant contributor to spalling included measured results showing that pore pressure does not immediately dissipate to zero at a crack or gap in the concrete. Instead, pore pressure bridges the gap by experiencing a slight decrease, and then continues to build up again. Additional support came from laboratory results accentuating the success of reduced, or no spalling when polypropylene fibers are added to HSC mixtures. Since the introduction of fibers would not have been expected to relieve thermal stresses, it follows that the relief of pore pressure must have been paramount in the improved spalling behavior. This behavior needs to be further investigated to better understand the process of how and why fibers are effective in this capacity. It was agreed that subsequent modeling of HSC for heat and mass transfer should be done in consideration of the cases with and without polymeric fibers.

(b) Investigation of new numerical methods to handle the saturated-unsaturated interface zone

Discussion: The success in handling numerical modeling difficulties that occur at the sharp liquid-vapor interface (saturated-unsaturated) zone in concrete when heat is applied varies with different numerical techniques used. Philosophical differences expressed in the workshop on how to adequately handle this zone from a numerical standpoint indicated the need for detailed examination of existing numerical methods such as the ones successfully used in Ahmed's model [Ahmed, 1995] and, perhaps, their modification or the development of new methods.

(2) Thermal stress analysis with inclusion of fracture mechanics

Discussion: At present, a consensus with regard to what is the principal cause, between thermal stresses and pore pressure effects, for the spalling of fire-exposed HSC has not been reached. Analysis of internal stresses in HSC elements, caused either by thermal stresses or pore pressure buildup, with consideration of other factors such as creep and shrinkage must be made in order to determine the relative importance of thermal stresses and pore pressure, on the tendency for spalling in fire-exposed HSC. Fracture mechanics principles may be necessary to predict cracking.

(3) Coupling of pore pressure and fracture process

Discussion: Accurately measuring and predicting pore pressure buildup during a fire situation is not enough. Pore pressures must be quantitatively linked to spalling of concrete. Experimental data showing that pore pressure does not drop to zero when a crack forms led to a new approach in analyzing the initiation of spalling. Thus modeling to predict spalling should include the effect of cracking and interaction between the pore pressure and the crack.

(4) Coordination with other groups regarding material and element testing

Discussion: In order to be able to predict pore pressures and thermal stresses at fire temperatures, and link these to a methodology for determining concrete damage, various material properties must be known. Measurements that must be made include material strengths at elevated temperatures, specific heat and thermal conductivity, density, initial moisture content, porosity and permeability, sorption isotherms, mass loss with temperature along with the effect of heating rate, validation tests of fracture including size effect, moisture migration measurements, pore pressure measurements, effect of fibers on porosity and permeability (polypropylene and other polymeric fibers), fracture properties at high temperature and different amounts of saturation, plasticity of concrete-filled steel tube columns at elevated temperatures, and data bases for tests of fracture and other size effects. This list of activities needs to be cross-referenced with those of the other working groups for inclusion of additional tests.

3.4 Working Group C: Codes and Standards

3.4.1 Introduction:

Research needs on fire performance of HSC that are in the domain of codes and standards were identified by this working group, and are described and discussed in this section. Working group C: *Codes and Standards* was composed of the following members:

J.A. Milke (Chair)	University of Maryland	U.S.A.
L.T. Phan (Recorder)	NIST	U.S.A.
W. Jones	NIST	U.S.A.
J. Messersmith	Portland Cement Association	U.S.A.
V. Karthigeyan	HSB-OSD (Health and Safety)	U.K.
L.W. Bell	Fibermesh	U.S.A.

3.4.2 Research Needs:

(1) Standard Test Protocols for Determining Engineering Properties of Fire-Exposed HSC

Discussion: Most current engineering properties data at elevated temperature were obtained by testing HSC specimens using different heating rates, specimen sizes and shapes, and loading histories. These differences may result in incompatible test results, especially for HSC since the rate of pore pressure buildup and the moisture escape path affect the performance of the test specimen. In order to permit the comparison of data from different laboratories, it will be necessary to establish a suite of standard test methods. These test methods will consider the differences between transient and steady-state tests, and between properties measured at elevated temperatures versus those measured at room-temperature after heating (residual properties). Guidelines will need to be developed on which types of tests should be used for different purposes.

(2) Mechanical Properties-Temperature Design Curves for HSC

Discussion: At present, the most used concrete strength and modulus of elasticity-temperature relationships are those prescribed by the Eurocodes [CEN ENV 1994-1-2] and recommended by RILEM Committee 44-PHT [CEB Bulletin D'Information N° 208]. These design curves were based mostly on experimental data of normal strength concrete and are useful for estimating mechanical properties of NSC exposed to high temperature. However, these design curves have been shown to be unconservative when applied to HSC [Phan, 1996]. On the other hand, the Finnish Code [High Strength Concrete, *Supplemental Rules* and Fire Design *RakMK B4*] prescribes a strength-temperature design curve specifically for HSC with compressive strength in the range of 70 MPa to 100 MPa. This design curve is applicable for both *stressed* (preload of up to 30% of room temperature compressvie strength) and *unstressed* test conditions. A comparison with existing test data shows that, while the Finnish strength-temperature curve is more applicable to HSC than those prescribed by the Eurocodes, it is still slightly unconservative in the temperature range of 200 °C to

400 °C, especially for the case of *unstressed* test of HSC with lightweight aggregate. Mechanical properties-temperature design curves, similar to those prescribed by the Finnish and Eurocodes, should be incorporated into U.S. codes to aid in fire design of HSC structures. These curves might include modification factors to account for variations such as different aggregate types used in the United States. Such design curves are also helpful for assessing the residual strength of HSC after a fire. Additional data are required to develop reliable design curves.

(3) Guidelines for Interpretation of HSC Material Tests and Standard Fire Tests

Discussion: Engineering properties of HSC at elevated temperature are obtained by testing HSC cylinders or prisms. The measured properties are typically related to the temperature measured at the center of the specimens and are dependent on, among other things, heating rate. Whereas the current standard fire tests, such as ASTM E 119 and ASTM E 1529, prescribe procedures for fire testing of structural assemblies by subjecting the assemblies to standard temperature histories. These standard temperature histories characterize the ambient environment inside the test chamber, but not necessarily the temperature and the rate of temperature development within the test assemblies. Thus the results of these two types of tests are not directly comparable. Guidelines should be developed to permit the comparison of the results of these tests so that the measured engineering properties, obtained from cylinder or prism tests, can be used to explain the fundamental behavior of the structural assemblies when tested in accordance with these ASTM standard fire tests.

(4) Guidelines for Selecting Realistic Design Fire Exposures

Discussion: At present, ASTM E 119 and E 1529, ISO 834, and JIS A 1304 prescribe fire testing of structural assemblies using standard temperature histories that are characterized by a controlled heating rate. These standard fire exposures do not represent likely temperature histories of real fires. As a result, the fire exposure conditions specified in these standard test methods are not necessarily representative of the conditions that may exist in real fires. With the current tendency of moving towards performance-based standards, it is necessary to provide guidance for the selection of realistic design fire exposures which are particularly suitable for the specific HSC structure being evaluated.

(5) Guidelines for Fire Design of HSC Structural Elements

Discussion: Guidelines for the fire design of HSC structural elements, which allow the calculation or assessment of the fire resistance period and load carrying capacity of structural elements, are not available in U.S. codes and standards. Such guidelines are needed for fire design of HSC structures and should incorporate the different responses due to differences in structural element types (beam, column, wall, or slab), HSC engineering properties, applied loads, and HSC spalling characteristics.

(6) Design Guidelines to Mitigate Spalling in Fire-Exposed HSC

Discussion: Limited experimental studies have shown that the risk of explosive spalling in fire exposed HSC can be reduced by using appropriate design detailing, such as optimal sizes and spacing of transverse reinforcement, concrete cover, etc., and additions to the concrete such as steel and polypropylene fibers. The effects of these design details and mixture additions should be studied and results should be incorporated into design guidelines to reduce the risk of explosive spalling in HSC structures during a fire.

4. RELEVANT RESEARCH PROGRAMS WORLDWIDE

4.1 Introduction

Prior to the workshop in February, NIST staff contacted researchers from various laboratories worldwide to request information on research activities relevant to the subject of performance of HSC at elevated temperatures. The feedback came from researchers, many of whom were able to attend the workshop, in laboratories of 11 countries, including Sweden, Italy, Germany, France, Canada, Taiwan, United Kingdom, Norway, Finland, Australia, and the United States. This chapter provides general information on these research programs as well as points of contact from whom additional information on the respective research programs may be obtained. Both recently completed and on-going projects within each research program are listed.

4.2 Organizations Performing Research and Descriptions of Research Programs

4.2.1 Fire Safety Design (FSD), Lund, Sweden

Program Description

As part of the Swedish national project on High Performance Concrete (HPC), FSD has been working on Fire Performance of HPC since 1992 and is now finishing the work by developing fire design methods for HPC beams, slabs, and columns. In the project numerous fire tests have been performed on small HPC specimens and structural elements. The objectives are to investigate, assess, or develop:

- The risk and tendency of spalling of HPC specimens at different heating rates and load levels for various concrete mixtures.
- The influence of polypropylene fibers on spalling tendency.
- Thermal properties as a function of temperature for the development of analytical expressions.
- Material properties and constitutive laws.
- Analytical simulations of small HPC test specimens.
- Analytical simulations of fire tested HPC columns.
- Fire design methods for HPC beams, slabs, and columns.

Contact Person:

Dr. Yngve Anderberg
Fire Safety Design
P.O. Box 2170
S-22002 LUND, Sweden
FAX: 46-46-140030
Tel: 46-46-140020
E-mail: *yngve.anderberg@fsd.se*

4.2.2 Milan University of Technology, Milan, Italy

Program Description:

As part of a joint Research Project financed by the European Communities and a number of industrial partners and research institutions (the Italian National Agency for Energy, New Technologies and Environment - ENEA), a multi-faceted research program is in progress in Milan to study the fire performance of siliceous HSC (f_c = 72 MPa to 95 MPa) and special microconcretes (Reactive Powder Concretes and Compact Reinforced Concretes, f_c = 170MPa to 200 MPa). The objectives are to (1) measure the complete stress-strain curves, in compression and in tension, of HSC at room and elevated temperatures (up to 500 °C); and (2) evaluate HSC fracture parameters (fracture energy, characteristic length, toughness index) as a function of temperature. Both the material and the structural behavior are investigated, since the thermally-induced softening of concrete favors stress redistribution in a structure, making the overall structural behavior less sensitive to high temperature than the material itself. The project consists of four phases:

(1) Compression and tension behavior of flint-based HSC: residual properties after a cycle at 105°C, 250°C, 400°C and 500°C (heating and cooling in quasi-steady conditions, with 12 hours at the maximum temperature), notched (tension) and unnotched (compression) cylinders (f_c = 72 MPa and 95 MPa).
(2) Deep beams subjected to 3-point bending and circular slabs subjected to punching (both reinforced and unreinforced): residual capacity (load-displacement behavior included) after a thermal cycle at 105°C, 250°C and 400°C (flint-based concrete with f_c = 72 MPa).
(3) Fracture behavior of flint based HSC (f_c = 72 MPa and 95 MPa): evaluation of the fracture energy per unit volume in the case of multiple or distributed cracking (pied prisms, for evaluating the damage density in tension and the characteristic length) after a cycle at high-temperature (T = 105 °C-400 °C).
(4) Tension behavior of one high-strength calcareous concrete (f_c = 95 MPa) and of two very high-strength fiber-reinforced microconcretes: the stress-strain and stress-crack opening curves will be determined at high temperature (T = 105 °C-400 °C). Special dumbbell-shaped and notched specimens have been cast in order to make it possible to extract the measures from the specimens loaded inside the furnace; the specimens are provided with special threaded ends that permit their attachment to the testing machine platens; the tests will be displacement-controlled, as in all previous cases. This phase of the project is being carried out in close collaboration with Prof. Gabriel A. Khoury at the Department of Civil Engineering of Imperial College in London. Further tests regarding the residual behavior after the thermal cycle will be carried out in Milan, as well as most of the data processing.

Phases 1 and 2 are completed, Phase 3 is well advanced, and Phase 4 is in the initial stage.

Contact Persons: Professors Roberto Felicetti and Pietro G. Gambarova
Politecnico Di Milano
Dipartimento Di Ingegneria Strutturale
Piazza Leonardo da Vinci, 32
20133 Milano, Italy
Fax: 011-39-2-23994220
Tel: +39-2-2399-4391

4.2.3 Institut für Baustoffe, Massivbau und Brandschutz (IBMB), Braunschweig, Germany

Program Description:

- Joint project BRITE EURAM program (HITECO), funded by the European Community to develop "*understanding and industrial applications of high performance concretes in high temperature environments.*" Industrial and research institute partners include: Bouygues (France), ENEA (Italy), Aalborg Portland Cement (Denmark), VTT (Finland), Imperial College (England), PARTEK (Finland), CSIC (Spain), and Padova Ricerche (Italy). Program duration is three years, from 1996 to 1998. Materials studied include 90 MPa -100 MPa HPC and ultra high performance concrete (UHPC) with strength of at least 150 MPa. Program deliverables include: Software, spalling indicators, description of mechanical behavior, and prenormative recommendations.

- Completed project concerning fire behavior of HSC elements under Compression - Elaboration of Calculation Bases for the Load Bearing and Deformation Behavior. This project was funded by the German Industry Research and Development Foundation (AiF) and the Federal Ministry of Economics. The result is proprietary and reported in German.

- Completed investigations of thermal and mechanical characteristics of HSC exposed to fire (Diploma work by Carsten Schwarz, IBMB/MPA Braunschweig, in German).

Contact Person: Dr. Ulrich Diederichs
Amtliche Materialprüfanstalt für das Bauwesen
Beethovenstraβe 52
D-38106 Brauschweig, Germany
FAX: 49 531 391 4573
Tel: 49 531 391 5426

4.2.4 Portland Cement Association, U.S.A

Program Description:

- The project High-Temperature Properties of High-Performance Concrete was being conducted by Construction Technology Laboratories (CTL) and was scheduled to be completed by early 1997. In this project, 76 mm x 150 mm cylinders, of representative HPC mixtures, 69 MPa to 148 MPa, were to be cast and such parameters as permeability, rate of drying, moisture content, and strength development were to be measured. These samples were to be subjected to a number of different high-temperature exposures. Factors such as strength degradation, stiffness changes, spalling potential, and moisture movement were to be measured on specimens that are restrained and unrestrained during heating. Measurements were to be taken at elevated temperatures as well as on specimens allowed to return to ambient temperatures. These data will allow for the development of models of high-temperature material behavior of HPC.

Contact Person:

Mr. Ronald G. Burg
Construction Technology Laboratories
5420 Old Orchard Rd
Skokie, Illinois 60077
FAX: 847 965 6541
Tel: 847 965 7500
E-mail: *rburg@c-t-l.com*

Program Description:

- A Full-scale HSC column fire test program is to be conducted by PCA. The concrete will include carbonate and siliceous aggregates. Six columns have been tested with at least three more planned. There is a possibility of a fourth column being tested containing polypropylene fibers. Test results are scheduled to become available at the end of 1997.

- A project was completed in 1996 on the thermal properties of carbonate aggregate HSC at elevated temperatures. PCA R&D Serial No. 2031 was published to summarize the project. The report includes results of measurements of thermal conductivity, thermal diffusivity, and mass loss at elevated temperatures.

- PCA Publication RD104T (1994), "Engineering Properties of Commercially Available High-Strength Concretes (Including Three-Year Data)" summarizes the results of a non-fire related test program.

- Fire endurance of carbonate aggregate HSC slabs: A paper was published in the ACI Materials Journal (March-April 1988). It compares the fire resistance of HSC slabs with those of normal strength concretes. The fire resistance is based on the heat transmission criteria in ASTM E119.

Contact Person: Mr. James P. Hurst
Portland Cement Association
5420 Old Orchard Rd.
Skokie, Illinois 60077
FAX: 847 966 9781
Tel: 847 966 6200
E-mail: *jim_hurst@portcement.org*

4.2.5 Laboratoire Central des Ponts et Chaussees (LCPC), France

Program Description:

- French National Research Project "BHP 2000" ("HPC 2000"), Work-Group 2: "Tenue Au Feu (Fire Resistance)". Project in progress:

  - Comportement des Beton Haute Performance vis-a-vis de L'eclatement - Modelisation (Spalling Behavior of HPC - Modelling), by C. Casselman and O. Corydon, I.P.S.N.
  - Proprietes des BHP a Hautes Temperatures - Etude Bibliographique (Properties of HPC at High Temperatures - Literature Survey), by P. Pimienta and A. Leduff, CSTB.
  - Modelisation du Comportement des BHP vis-vis-vis de L'eclatement - Etudes en Laboratoire et Determination des Caracteristiques Necessaires au Modele, Rapport D'etape (Modelling Spalling Behavior of HPC - Experimental Study and Determination of Modelling Characteristics, Progress Report), by P. Kalifa, CSTB.

- Assessment and repair of damage due to fire in the Channel Tunnel in 1996. Project in progress. States of the materials before and after the fire are examined.

- Physical mechanisms and modeling of the behavior of concrete at high temperature. Project being planned.

- European Research Program on Nuclear Fission Safety: "Containment Evaluation Under Severe Accident."

Contact Person: Dr. Franz-Josef Ulm
Div. Betons et Ciments pour Ouvrages d'Art
Laboratoire Central des Ponts et Chaussees (LCPC)
58, bd Lefebvre
75732 Paris Cedex 15, France
FAX: 33(1) 40 43 54 98
Tel: 33(1) 40 43 150
E-mail: *ulm@inrets.fr*

4.2.6 Rutgers University, U.S.A.

Program Description:

An experimental laboratory facility is being set up in the Department of Civil and Environmental Engineering at Rutgers University for the purpose of measuring pore pressures and temperatures in moist high- strength concrete exposed to elevated temperatures. This laboratory is scheduled to become operational in the summer of 1997 and will provide experimental data needed to refine numerical analyses. At present, numerical simulations are being conducted to study several key aspects of the performance of high-strength concrete in fires.

Contact Person:
Professor Gary R. Consolazio
Rutgers University
Dept. Of Civil & Environmental Engineering
P.O. Box 909
Piscataway, NJ 08855
FAX: 908 445 0577
Tel: 908 445 4414
E-mail: *grc@civeng.rutgers.edu*

4.2.7 University of Missouri-Rolla, U.S.A.

Program Description:

Under the auspices of the American Iron and Steel Institute (AISI), three projects are ongoing at the University of Missouri-Rolla:

- The simulation of explosive spalling of refractory concrete (calcium aluminate based).
- The measurement of air permeability of refractory concretes using a vacuum decay method. Permeability changes are being measured as a function of:

  a) thermal treatment
  b) concrete composition (original mixture)
  c) additives including chemicals and polymeric fibers

- "Postmortems" of large specimens exposed to one-sided heating involving measurement of key properties along the thermal gradient and explaining the relationships between thermal gradient and texture/property gradients.

AISI quarterly reports are confidential but a recent summary has been published. Comparable work on refractory concretes is unknown at this time.

Contact Person: Professor Robert E. Moore
University of Missouri-Rolla
Ceramic Engineering
278 McNutt Hall
Rolla, MO 65401
FAX: 573 341 6934
Tel: 573 341 6326
E-mail: *rmoore@umr.edu*

4.2.8 National Research Council-Canada (NRCC)

Program Description:

- An experimental and analytical project, which aims to develop design guidelines for fire design of HSC columns for incorporation into the National Building Code of Canada, is being undertaken by the NRCC in collaboration with industry (PCA, CPCA), research organizations such as Concrete Canada (a Center of Excellence of the Canadian government) and the National Chiao Tung University (NCTU) in Taiwan. As part of this project, 48 reinforced HSC columns are being fabricated and tested. These include 20 plain HSC columns and 28 fiber reinforced HSC columns. Both steel and polypropylene fibers are being considered (8 columns include steel fibers and 20 columns include polypropylene fibers). The 28-day compressive strength is about 90 MPa. Both silicious and carbonate aggregates concrete are used. The full-scale columns will be subjected to the standard time-temperature curve given by ASTM E119. Variables to be studied include section sizes, shapes (circular and square), spacing of the ties, load intensities, as well as the end support conditions.

- Fire tests were conducted on HSC-filled steel columns. This project was conducted to quantify the effect of the type of concrete on the fire resistance of concrete filled steel columns. Three types of columns were studied: (1) filled with plain concrete; (2) filled with concrete reinforced with traditional bars; and (3) filled with steel fiber reinforced concrete (1.75% fibers by mass). Both normal strength (40 MPa) and HSC (80 Mpa to 90 MPa) were used in the experimental as well as numerical studies. Circular and square cross sections were considered. Upon completion of the tests on the normal strength concrete filled columns and numerical studies, design guidelines will be incorporated into the Canadian building code.

Contact Person: Dr. Venkatesh Kodur
National Research Council/Canada
Institute for Research in Construction
M-59, Montreal Road
Ottawa, Ontario, Canada ,K1A 0R6
FAX: 613 954 0483
Tel: 613 993 9729
E-mail: *venkatesh.kodur@nrc.ca*

4.2.9 Fire Laboratory of Architecture and Building Research Institute (ABRI), Taiwan

Program Description:

A National Research Council-Canada/National Chiao Tung University (NRCC/NCTU) joint test program on fire performance of HPC is being conducted. The current project is for 3 years (1996-1999). The collaboration calls for the NRCC to provide about 300 HSC cylinders (100 mm by 200 mm, minimum strength of 70 MPa) for high temperature stress-strain tests at the NCTU in Taiwan. The NCTU is to fabricate 15 full-scale HSC columns and to ship the columns to the NRCC for load and fire resistance tests in Canada.

The NRCC cylinders are made of siliceous aggregate, siliceous aggregate plus steel fibers, carbonate aggregate, and carbonate aggregate plus steel fiber. The NCTU columns have square cross sections (305 mm x 305 mm x 3810 mm) and concrete strength exceeding 70 MPa. The concretes include siliceous aggregates, carbonate aggregates, steel fibers, glass fibers, and polypropylene fibers in various combinations.

Contact Person:

Dr. T.D. Lin
2022 Hollywood Ct.
Wilmette, Il 60091
FAX: 847 251 8090
Tel: 847 251 8071

Dr. Sam Chou
Director, Fire Laboratory
Architecture and Building Research Institute
Taiwan

4.2.10 City University, London, U.K.

Program Description:

A three year national research program on explosive spalling of high strength concrete at fire temperatures using different types of aggregates, curing regimes, strengths and restraint conditions is being conducted at the City University in London. Fire testing is being carried out in conjunction with the U.K.'s Building Research Establishment (BRE).

Contact Person:

Dr. Patrick J.E. Sullivan
Sullivan & Associates
2 Sandy Lodge Rd.
Rickmansworth Herts, WD3 1LJ
England
FAX: 923897484
Tel: 923773267
E-mail: *P.J.E.Sullivan@city.ac.uk*

4.2.11 SINTEF, Norway

Program Description:

Completed and on-going research activities on fire-exposed HSC by SINTEF include:

- Offshore concrete exposed to hydrocarbon fire (1985-1987)
- Explosion and fire protection (1984-1988)
- High-Strength Concrete. Phase 3: Fire resistance (1986-1993)
- LWA Concrete for floating platforms (1990-1992)
- Fire research on high-strength LWA concrete, and RC structures with nonmetallic reinforcement (in progress)

Contact Person:
Dr.Techn. Jens Jacob Jensen
SINTEF Civil and Environmental Engineering
Cement and Concrete
N-7034 Trondheim, Norway
FAX: 47 73 59 71 36
Tel: 47 73 59 45 31
E-mail: *jens.jensen@civil.sintef.no*

4.2.12 VTT, Finland

Program Description:

Under the auspices of the joint European BRITE EURAM project (HITECO, see also section 4.2.3), Finland is presently (1996-1998) investigating the fire performance of HSC (60 MPa to 100 MPa) and ultra high strength concrete (UHPC, exceeding 150 MPa). Thermal and mechanical properties, as well as spalling characteristics of small specimens are being studied for material models development. Fire tests on short columns and other structural members are also planned.

Contact Person:
Ms. Ulla-Maija Jumppanen
VTT Building Technology, Fire Technology Laboratory
Technical Research Center of Finland
P.O. Box 1803, FIN - 02044 VTT
Finland
FAX: 3589 456 4815
Tel: 3589 456 4792
E-mail: *ulla-maija.jumppanen@vtt.fi*

4.2.13 Monash University, Australia

Program Description:

- *Experimental study to evaluate a mathematical model for the behavior of reinforced concrete walls in fire.* The increasing use of concrete walls as load carrying structural members, mainly in the form of tiltup and precast walls, is allowing structural engineers to design increasingly efficient and economical structures for buildings. The fire resistance requirements for structural adequacy embodied in the Australian concrete structures design code (AS3600-1994) are based partly on results generated by a computer-based mathematical model and partly from experience. There have been no experimental studies to substantiate either the mathematical model or the current design guidelines. Moreover, through discussions with consulting engineers, precast concrete manufacturers and concrete associations, it is apparent that the design guidelines for structural adequacy are restrictive. This project aims to experimentally study the performance of slender, reinforced concrete wal1s under standard fire conditions. It is anticipated that the experimental tests will be completed by the end of 1997.

  An agreement has been reached with BEP Melbourne Research Laboratories (BHP-MRL) that will allow researchers to use the BHP-MRL fire testing facilities to perform the experimental tests. The gas-fired furnace to be used is 5.1 m long, 2.5 m wide and 2 m tall. A total of eight fire tests are to be conducted in the current testing program.

  Each wall thickness (75 mm, 100 mm and 150 mm) will be tested with a central layer of 0.25% total reinforcement, while the l50 mm wall will be tested with two layers of reinforcement at a total reinforcement content of 0.25%. Each set of four walls will be tested using 40 MPa concrete (normal strength) and 100 MPa concrete (high strength). A special purpose test-rig has been constructed that will apply eccentric compression to the horizontally mounted test specimens. Thus lateral load effects are also being studied. The test specimens will be subject to the IS0834 standard fire environment on one side only, which is representative of a compartment fire within a building. One-way bending action of the test specimens is being studied.

  During the fire tests of loaded specimens, an investigation of several parameters likely to influence spalling of high strength concrete will be conducted. In addition to the loaded test specimens, unloaded spalling test specimens will be fire tested. Reinforcement contents of the spalling test specimens will be identical to the reinforcement contents of the loaded test specimens. The moisture content of representative samples of concrete will be assessed prior to testing the specimens. The parameters to be initially studied in the spalling investigation include:

  - total slab thickness: 75 mm, l00 mm and 150 mm
  - cover to reinforcement: 25 mm, 38 mm, 50 mm and 75 mm.
  - concrete strength: 40 MPa and 100 MPa

The results of the experimental study will be used to develop an appropriate mathematical model to numerically simulate the structural response of concrete walls in fires. Following extensive parametric studies, this mathematical model will be used in the development of more rationally based guidelines for the design of reinforced concrete walls in fire.

A second key component of the current research program is a detailed study of heat and mass transfer characteristics of concrete slabs in fires. It is envisaged to verify experimentally measured pore pressures and temperatures in heated HSC slabs with those predicted by computer-based heat and mass transfer models.

- *Evaluation of the high temperature mechanical properties of high strength concrete.* The conclusions drawn from the recent workshop on the fire performance of high strength concrete (HSC) suggest that there is insufficient experimental data on fire exposed HSC. Furthermore, the increased usage of HSC in structural applications must recognize the fundamental behavioral differences of HSC compared with normal strength concrete.

  To address the deficiency of experimental data on fire exposed HSC, a major research effort is being planned at Monash University, Australia. This research program aims to develop a better understanding of the behavior of fire exposed HSC and to develop suitable constitutive relationships for calculating the structural strength of fire exposed HSC members. The Department of Civil Engineering at Monash University will shortly take delivery of a new electrically powered furnace. The furnace will enable heating rates up to 40 °C/min to be attained (approaching those of standard temperature-time curves). The configuration of the furnace will allow researchers to study both cylinders (100 mm diameter by 200 mm long) and beams (100 mm x 100 mm x 450 mm long). External load is applied via high temperature and stress resistant advanced structural ceramic rams connected to either a 5000 kN Amsler compression testing machine or a 500 kN Baldwin testing machine. With this configuration, three types of high temperature tests can be conducted, i.e., unstressed, stressed or unstressed residual, thus allowing a complete study of fire exposed HSC at all stages of structural life.

  At present, the research program is in its initial stages. A number of tests are planned for late 1997 to assess the capabilities of the furnace. The initial tests planned include:

  - unstressed tests on HSC cylinders to establish variations in compressive strength with temperature.
  - unstressed residual strength tests on model size reinforced concrete beams to establish the criteria for bond induced failure or flexure induced failure in fire damaged concrete beams. Also, suitable design equations to predict the failure load of beams will be developed.

  Additional funding is currently being sought through local sources to equip the furnace with high temperature strain measurement equipment to enable concrete deformation to be recorded during the tests. Such data are fundamental to the development of suitable constitutive relationships for fire-exposed HSC.

Contact Persons:

Dr. Jay G. Sanjayan
Department of Civil Engineering
Monash University
Clayton, Australia
Tel: 61 3 9905 4985
Fax: 61 3 9905 4944
Email: sanjay@eng.monash.edu.au

Mr. Damian A. Crozier
Department of Civil Engineering
Monash University
Clayton, Australia
Tel: 61 3 9905 4958
Fax: 61 3 9905 4944
Email: crozier@eng.monash.edu.au

5. ACKNOWLEDGMENTS

The editors express sincere appreciation to all workshop participants whose contributions made the workshop a successful event. Special thanks are extended to the Working Group (WG) Chairs and Co-chairs, Dr. Y. Anderberg and Mr. M.P. Gillen (WG A-1), Dr. U. Diederichs and Mr. R.G. Burg (WG A-2), Mr. J.P. Hurst (WG B), and Dr. J.A. Milke (WG C), for their diligence in guiding the discussions of their respective working groups and for presenting succinct summaries at the plenary session. Special thanks are also extended to all distinguished researchers who made presentations at the workshop and who provided these proceedings with technical papers. We thank Dr. V. Kodur of the National Research Council - Canada for agreeing to serve as the external reviewer of this document, and all those individuals who contributed to the review and submitted constructive suggestions. We thank Dr. George C. Hoff, Mr. M.P. Gillen, and Dr. S.K. Ghosh for their assistance in organizing this workshop. Finally, we thank Dr. Jack E. Snell for his welcoming remarks to open the workshop.

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Phan, L.T., "*Fire Performance of High-Strength Concrete: A Report of the State-of-the-Art*," NISTIR 5934, National Institute of Standards and Technology, December, 1996, Gaithersburg, MD.

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APPENDIX A. Workshop Agenda/List of Participants/Lists of Working Group Members

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A.1 Workshop Agenda

Agenda

NIST Workshop on Fire Performance of High-Strength Concrete

National Institute of Standards and Technology

Building and Fire Research Laboratory

Thursday, February 13, 1997

7:45 am - 8:15 am — **Registration (NIST, Lecture Room E)**

8:15 am - 2:30 am — **Introduction and Technical Presentations (NIST, Lecture Room E)**

Welcome	Dr. Jack Snell, Deputy Director, Building and Fire Research Laboratory, NIST
Goal of Workshop	Dr. Nicholas J. Carino, Leader, Structural Evaluation Group, BFRL, NIST
Presentations	Dr. Long T. Phan, BFRL, NIST, Session Chairman
8:30 - 8:50	"*High-Strength Concrete in Germany. Utilization, Research and Standardization*" U. Diederichs, Technische Universität Braunschweig, Germany.
8:50 - 9:10	"*Fire Test of Normal-Weight/High Performance Concrete in Taiwan*" T.D. Lin, Fire Laboratory, ABRI, Taiwan.
9:10 - 9:30	"*Fire Resistance and Residual Strength of High-Strength Concrete Exposed to Hydrocarbon Fire*" J.J. Jensen, SINTEF, Norway.
9:30 - 9:50	"*Spalling Phenomena of HPC*" Y. Anderberg, Sweden.
9:50 - 10:00	*"Fire Damage in the Channel Tunnel"* Franz-Josef Ulm, LCPC, France.
10:00 - 10:30	**Coffee Break**

Thursday, February 13, 1997 (Continued)

10:30 - 10:50	"*Research Activities in Finland on Fire Resistance of HSC*" U.-M. Jumppanen, VTT, Finland
10:50 - 11:10	"*Studies on the Fire Resistance of HPC at the National Research Council/Canada*" V. Kodur, NRC/Canada
11:10 - 11:30	"*Spalling of High-Strength LWA Concrete - Cause and Cure*" M.P. Gillen, Dupont Engineering
11:30 - 11:50	"*Limitations of Current U.S. Standards and Challenges for Proposed Performance-Based Standards*" J.A. Milke, University of Maryland
12:00 pm - 1:00 pm	**Lunch**
1:00 pm - 1:20 pm	"*Computational Modeling of Temperature, Pore Pressure, and Moisture Content in Concrete Exposed to Fire*" G. Ahmed, PCA
1:20 pm - 1:40 pm	"*Analysis of Pore Pressure, Thermal Stress, and Fracture of Concrete in Rapidly Heated Concrete*" Z.P. Bazănt, Northwestern University.
1:40 pm - 2:00 pm	"*Fire Tests on Normal and High-Strength Reinforced Concrete Columns*" C.-M. Aldea, Northwestern University.
2:00 pm - 2:20 pm	"*Measurement and Prediction of Pore Pressure in Cement Mortar Subjected to Elevated Temperature*" G. Consolazio, Rutgers University.
2:30 pm - 3:00 pm	**Coffee Break**
3:00 pm - 5:30 pm	**Concurrent Working Group Meetings**

	WG: A-1 **Material Tests**	**WG: A-2** **Element Tests**	**WG: B** **Analytical Studies**	**WG: C** **Codes & Standards**
Chair:	Y. Anderberg	U. Diederichs	J.P. Hurst	A. Milke
Co-Chair:	M.P. Gillen	R.G. Burg		
Recorder:	N.J. Carino	D. Duthinh	E. Garboczi	L.T. Phan

Friday, February 14, 1997

8:30 am - 12:00 pm **Concurrent Working Group Meeting**

	WG: A-1 Material Tests	WG: A-2 Element Tests	WG: B Analytical Studies	WG: C Codes & Standards
Chair:	Y. Anderberg	U. Diederichs	J.P. Hurst	J.A. Milke
Co-Chair:	M.P. Gillen	R.G. Burg		
Recorder:	N.J. Carino	D. Duthinh	E. Garboczi	L.T. Phan

8:30 - 10:00 Working Group Discussions

10:00 - 10:15 **Coffee Break**

10:15 - 12:00 Working Group Discussions

12:00 pm - 1:00 pm **Lunch**

1:00 pm - 3:00 pm **Plenary Session (Lecture Room E)**
Summary of Working Group Recommendations
Concluding Remarks

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A.2 Workshop Participants

NIST Workshop on Fire Performance of High-Strength Concrete
February 13-14, 1997
List of Participants

Organizing Committee Members

Nicholas J. Carino
Building & Fire Research Laboratory, NIST
Building 226, Room B158
Gaithersburg, Maryland 20899
Tel: (301) 975-6063
FAX: (301) 869-6275
E-mail: *nicholas.carino@nist.gov*

S.K. Ghosh
Engineering Services, Codes and Standards
Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077-1083
Phone: (847) 966-6200, ext. 438
FAX: (847) 966-9781
Email: *s_ghosh@portcement.org*

Michael P. Gillen
Dupont Engineering
P.O. Box 80840
Wilmington, DE 19880-0840
FAX: 302 695 0734
Tel: 302 695 0250

George C. Hoff
Mobil Technology Company
Mobil Exploration & Producing Technical Center (MEPTEC)
Surface Engineering Department
13777 Midway Road
Dallas, TX 75244
FAX: 972 851 8349
Tel: 214 851 8774

H.S. Lew
Building & Fire Research Laboratory, NIST
Building 226, Room B168
Gaithersburg, Maryland 20899
Tel: (301) 975-6061
FAX: (301) 869-6275
E-mail: *hai.lew@nist.gov*

Long T. Phan
Building & Fire Research Laboratory, NIST
Building 226, Room B158
Gaithersburg, Maryland 20899
Tel: (301) 975-6077
FAX: (301) 869-6275
E-mail: *lphan@nist.gov*

Participating Members

Gamal N. Ahmed
Portland Cement Association
5420 Old Orchard Rd.
Skokie, Illinois 60077
FAX: 847 966 9781
Tel: 847 966 6200 x329
E-mail: *gamal_ahmed@portcement.org*

Corina-Maria Aldea
Northwestern University
NSF Center for S&T of ACBM
2145 Sheridan Rd., Room A130
Evanston, Il 60208-4400
FAX: 847 467 1078
Tel: 847 467 3630
E-mail: *cal569@hecky.acns.nwu.edu*

Yngve Anderberg
Fire Safety Design
P.O. Box 2170
S-22002 LUND, Sweden
FAX: 46-46-140030
Tel: 46-46-140020
E-mail: *yngve.anderberg@fsd.se*

Zdeněk P. Bazănt
Northwestern University
Department of Civil Engineering
Technological Institute
Evanston, Illinois 60208-3109
TEL. 847-491-4025 (secy. 847-491-3351)
FAX: 847-467-1078 (Dept. 847-491-4011)
E-MAIL: *z-bazant@nwu.edu*

Leonard W. Bell
Fibermesh, Div. Of Synthetic Industries
4019 Industry Drive
Chattanooga, Tennessee 37416
TEL: 423-892-7243
FAX: 423-499-0753

Dale Bentz
Building & Fire Research Laboratory, NIST
Building 226, Room B350
Gaithersburg, Maryland 20899
Tel: (301) 975-5865
FAX: (301) 990-6891
E-mail: *dale.bentz@nist.gov*

Alain Bilodeau
CANMET
405 Rochester Street
Ottawa, Ontario, Canada, K1A 0G1
FAX: 613 992 9389
Tel: 613 992 3806
E-mail: *alain.bilodeau@cc2smtp.nrcan.gc.ca*

Ronald G. Burg
Construction Technology Laboratories
5420 Old Orchard Rd.
Skokie, Illinois 60077
FAX: 847 965 6541
Tel: 847 965 7500
E-mail: *rburg@c-t-l.com*

James Clifton
Building & Fire Research Laboratory, NIST
Building 226, Room B350
Gaithersburg, Maryland 20899
Tel: (301) 975-6707
FAX: (301) 990-6891
E-mail: *james.clifton@nist.gov*

Gary R. Consolazio
Rutgers University
Dept. Of Civil & Environmental Engineering
P.O. Box 909
Piscataway, NJ 08855
FAX 908 445 0577
Tel: 908 445 4414
E-mail: *grc@civeng.rutgers.edu*

Leonard Cooper
Building & Fire Research Laboratory, NIST
Polymer Building, Room A249
Gaithersburg, Maryland 20899
Tel: (301) 975-6880
E-mail: *leonard.cooper@nist.gov*

Ulrich Diederichs
Amtliche Materialprüfanstalt für das Bauwesen
Beethovenstraβe 52
D-38106 Brauschweig, Germany
FAX: 49 531 391 4573
Tel: 49 531 391 5426

Dat Duthinh
Building & Fire Research Laboratory, NIST
Building 226, Room B158
Gaithersburg, Maryland 20899
Tel: (301) 975-4357
FAX: (301) 869-6275
E-mail: *dat.duthin@nist.gov*

William L. Gamble
University of Illinois
3122 Newmark Civil Engineering Laboratory
205 North Mathews
Urbana, Illinois 61801
FAX: 217 333 9464
Tel: 217 333 6935
E-mail: *w-gamble@uiuc.edu*

Edward Garboczi
Building & Fire Research Laboratory, NIST
Building 226, Room B350
Gaithersburg, Maryland 20899
Tel: (301) 975-6708
FAX: (301) 990-6891
E-mail: *edward.garbocz@nist.gov*

James P. Hurst
Portland Cement Association
5420 Old Orchard Rd.
Skokie, Illinois 60077
Tel: 847 966 6200
FAX: 847 966 9781
E-mail: *jim_hurst@portcement.org*

Jens Jacob Jensen
SINTEF Bygg og miljøteknikk
Strindveien 2
N-7034 Trondheim, Norway
Tel: 73-59-45-31
FAX: 47-7-359-7136
E-mail: *jens.jensen@civil.sintef.no*

Ulla-Maija Jumppanen
VTT Building Technology
Fire Technology Laboratory
Technical Research Center of Finland
P.O. Box 1803, FIN - 02044 VTT, Finland
Tel: 3589 456 4792
FAX: 3589 456 4815
E-mail: *ulla-maija.jumppanen@vtt.fi*

Victor Karthigeyan
Health and Safety Executive
No. 2 Rose Court
Southwark Bridge, London SE 1 9HS
United Kingdom
FAX: 44-171-717-6678
Tel: 44-171-717-6773
E-mail: *v.karthigeyan@hse.gov.uk*

Venkatesh Kodur
National Research Council/Canada
Institute for Research in Construction
M-59, Montreal Road
Ottawa, Ontario, Canada ,K1A 0R6
FAX: 613 954 0483
Tel: 613 993 9729
E-mail: *venkatesh.kodur@nrc.ca*

François de Larrard
Laboratoire Central des Ponts et Chaussees
Route de Bouaye/BP 19
44340 Bouguenais
FAX: 33 2 40 84 59 98
E-mail: *larrard@lcpc.fr*

T.D. Lin
Lintek Ltd.
2022 Hollywood Ct.
Wilmette, Il 60091
FAX: 847 251 8090
Tel: 847 251 8071

Nicos Martys
Building & Fire Research Laboratory, NIST
Building 226, Room B350
Gaithersburg, Maryland 20899
Tel: (301) 975-5915
FAX: (301) 990-6891
E-mail: *nicos.marty@nist.gov*

Jim Messersmith
Portland Cement Association
11479 Trimrose Ln.
Rockville, VA 23146
Tel: 804 749 3584
FAX: 804 749 3584

James A. Milke
University of Maryland at College Park
Department of Fire Protection Engineering
College Park, Maryland 20742
Tel: 301 405 3995
FAX: 301 405 9383
E-mail: *milke@eng.umd.edu*

Robert E. Moore
University of Missouri-Rolla
Ceramic Engineering
278 McNutt Hall
Rolla, MO 65401
Tel: 573 341 6326
FAX: 573 341 6934
E-mail: *rmoore@umr.edu*

Todd Sander
University of Missouri-Rolla
Ceramic Engineering
278 McNutt Hall
Rolla, MO 65401
Tel: 573 341 6326
FAX: 573 341 6934

Franz-Josef Ulm
Div. Betons et Ciments pour Ourages d'Art
Laboratoire Central des Ponts et Chaussees
58, bd Lefebvre
75732 Paris Cedex 15, France
Tel: 33(1) 40 43 150
FAX: 33(1) 40 43 54 98
E-mail: *ulm@inrets.fr*

A.3 List of Participants by Working Groups

NIST Workshop on Fire Performance of High-Strength Concrete
List of Participants by Working Groups

Organizing Committee Members
Nicholas J. Carino
George C. Hoff
H.S. Lew
S.K. Ghosh
Michael P. Gillen
Long T. Phan

Working Groups	A-1: Material Tests	A-2: Element Tests	B: Analytical Studies	C: Codes & Standards
Chair	Y. Anderberg	U. Diederichs	J.P. Hurst	J.A. Milke
Co-Chair	M.P. Gillen	R.G. Burg		
Recorder	N.J. Carino	Dat Duthinh	Ed Garboczi	L.T. Phan
Meeting Rooms	*Lecture Room E*	*Lecture Room F*	*Bldg. 225, Room B111*	*Bldg. 226, Room B317*
Participants	Y. Anderberg M.P. Gillen N.J. Carino Alain Bilodeau James Clifton U-M Jumppanen Robert E. Moore Todd Sander	U. Diederichs R.G. Burg George C. Hoff Dat Duthinh C-M Aldea W.L. Gamble Jens J. Jensen V. Karthigeyan** V. Kodur T.D. Lin L.W. Bell**	J.P. Hurst Ed Garboczi G. Ahmed Z.P. Bazant G.R. Consolazio L. Cooper N. Martys Franz-Josef Ulm	Walter Jones J.A. Milke L.T. Phan J. Messersmith V. Karthigeyan** L.W. Bell**

** participated in two Working Groups